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GEOLOGY OF THE MARYSVILLE BUTTES CALIFORNIA

BY

HOWEL WILLIAMS

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CALIFORNIA

BY

HOWEL WILLIAMS

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PLATES

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INTRODUCTION

Location of Area.—The Marysville Buttes (or Sutter Buttes, as they are often termed locally) lie between the Sacramento and Feather rivers, in Sutter County, California. Approximately, they are enclosed by the parallels 39°9′ and 39°18′ N, and the meridians 121°43′ and 121°55′ W, and occupy an almost circular area, ten miles in diameter. They are distant about twenty miles west of the foothills of the Sierra Nevada and some fifteen miles east of the Coast Range (fig. 1).

The Buttes are best approached through Marysville or Yuba City, situated about ten miles to the east, whence roads lead to the village of Sutter, and the smaller hamlets of West Butte and Pennington, conveniently located at the base of the hills.

The area is represented on the following maps:

1. U. S. Geological Survey, Marysville Folio, no. 17 (1895); scale, 1:125000; contour interval, 100 feet.

2. Marysville Buttes and vicinity, 1913; scale, 1:62500; contour interval, 25 feet.

3. Marysville Buttes Quadrangle, 1912; scale, 1:31680; contour interval, 5 feet to the 300-foot contour: 500, 1000, 1500, and 2000-foot contours sketched.

The maps (2) and (3) are published by the U. S. Geological Survey, the work having been done in cooperation with the State of California.

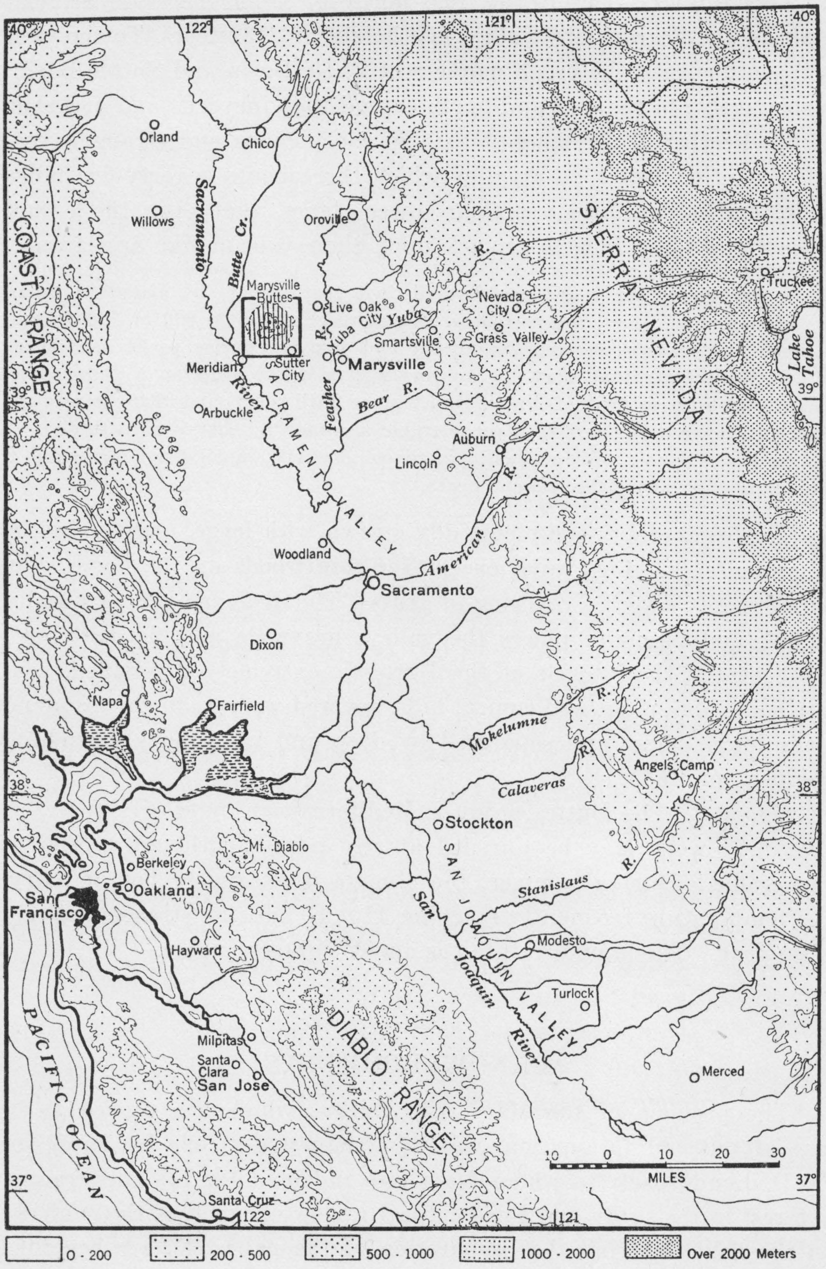

Fig. 1. Index map of a portion of California, showing the location of the Marysville Buttes.

Topography.—The Buttes rise abruptly from the wide alluvial plain of the Sacramento Valley to a height of 2132 feet. To the west and south spread the broad marshes of Butte Basin and Sutter Basin, respectively; to the east and north extend the vineyards and orchards of the Feather River flood-plain. So conspicuous and strangely isolated are the Buttes, in a valley which thereabouts is forty-five miles wide, and so uniform are their lower slopes, that even the casual passer-by seldom fails to remark upon their volcano-like appearance.

> In any view from a distance two distinct features of the mountain group are always noted; first, the peripheral slopes, reaching up to 600 or 700 feet in a long, gentle curve; second, the abrupt and jagged interior peaks and domes . . . It is probable that when the volcano was in active eruption it formed one great cone, such as that of Vesuvius, Etna, or Fuji-yama, and that its original form can be reconstructed with considerable accuracy by carrying up the curves of the lower slopes, with gradually increased declivity, until they culminate in a summit, high above the present peaks.[1]

The lower slopes are plentifully strewn with large, angular blocks of andesite (pl. 13*b*), and, except for thin woods on the north side, support only a sparse covering of grass. The drainage here is usually radial, and in many places the valleys are wide and flat-bottomed. By contrast, the interior of the Buttes is extremely diversified, consisting of high crags and conical hills, covered with small shrubs along their lower slopes and separated by deep and irregularly branching ravines (pl. 16*b*).

Climate.—The Buttes enjoy a Mediterranean type of climate, so that field work may be pursued at any period, although winter is preferable. During summer, the climate is extremely hot and dry, the temperature frequently reaching 115° F, and the streams entirely disappear. The annual rainfall is about eighteen inches.

ACKNOWLEDGMENTS

The problem of the Marysville Buttes, which has proved to be one of unusual fascination, was first suggested to me by Professor G. D. Louderback, to whom I am also indebted for his encouraging interest in the study and for a critical review of much of the evidence in the field. During the preparation of the paper, I have benefited by repeated discussion with Professor A. C. Lawson, many of whose valuable suggestions are embodied in the text. I am grateful to Dr. B. L. Clark for ever ready assistance in the identification of

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[1] Lindgren, W., U. S. Geol. Surv., Marysville Folio no. 17, 1895.

the fossils and of their stratigraphic value, and to Dr. V. T. Allen, the results of whose careful work among the Ione and related sediments of the adjacent Sierra Nevada alone made possible the interpretation of much of the sedimentary history and structure of the Marysville Buttes. Dr. F. A. Moss and Dr. A. Pabst have offered much welcome criticism both in the field and in the laboratory. It is a pleasure also to acknowledge my gratitude for the help given to me at the University by Dr. N. E. A. Hinds, Dr. N. L. Taliaferro, and Dr. C. A. Anderson. Finally, I desire to thank the Directors of the Commonwealth Fund for the generous favors which they have granted me during my tenure of one of their Fellowships and for the sympathetic interest which they have always shown in my work.

PREVIOUS LITERATURE

Although at an early stage, the work of the United States Geological Survey indicated that the Marysville Buttes present many interesting structural and volcanological problems, the literature concerning the area is almost wholly paleontological.

Perhaps the earliest reference is that made by Watts,[2] in which he recorded the presence of inflammable gas in the sandstones at the foot of South Butte, and of fossils at both South Butte and West Butte. The fossils were identified by Cooper as of Cretaceous age, in the sense defined by Gabb.[3] Additional species were cited by Cooper [4] in a subsequent paper.

Although the actual field work had been completed in 1892, it was not until 1895 that the Marysville Folio was published by the United States Geological Survey.[5] The Buttes were mapped by Lindgren; the adjacent foothills of the Sierra Nevada were studied by Turner. In the description of the quadrangle, Lindgren gives a succinct account of the Buttes, considering them to have been a volcano that was active ''at the close of the Neocene or the beginning of the Pleistocene. . . . probably a little later than the volcanoes which began their eruptions in the Sierra Nevada at the close of the Neocene.'' He recognized a threefold, more or less concentric division of the Buttes into:

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[2] Watts, W. L., The gas and petroleum yielding formations of the central valley of California. Calif. State Mining Bureau, Bull. 3, p. 9, August, 1894.

[3] Gabb, W. M., Geol. Surv. Calif., Palaeontology, vol. 1, p. 19, 1864.

[4] Cooper, J. G., Calif. State Mining Bureau, Bull. 3, pp. 39–44, September, 1894.

[5] Lindgren, W., *op. cit.*

a. A peripheral tuff ring.
b. An interior ring of upturned sedimentary rocks.
c. A central core of igneous rocks.

The sedimentary rocks were divided into a lower or Tejon formation (Eocene) and an upper or Ione formation (probably Miocene). Of these, the older rocks were distinguished only in the vicinity of West Butte, where they yielded abundant marine fossils, including the supposedly characteristic forms *Trochosmilia striata* Gabb and *Cardita planicosta* Lamarck. The younger beds were described as being more than 1000 feet thick, light-colored, soft, marine sandstones and clays, often carbonaceous and carrying impressions of leaves. They were considered to be the precise equivalents of the Ione beds exposed in the foothills of the Sierra Nevada, and thus to be either of early Neocene (Miocene) age, or, less probably, of later Neocene (Pliocene) age.

Lindgren found the central core of the Buttes to consist of a hornblende-mica andesite, apparently unlike any found on the western flank of the Sierra Nevada, associated with andesite breccia and with ''several rounded necks of rhyolite approaching a dacite in composition,'' the latter being regarded doubtfully as intrusive into the andesite. Impressed by the absence of dikes and lava flows, Lindgren concluded that

> . . . . the eruptions took the form of large masses or necks, forced upwards through the loose sediments. The mass and energy of the ascending lavas were so great that the surrounding sediments were uplifted more than 1000 feet and bent upwards on all sides of the necks. It is probable that the ascending lavas were very viscid and comparatively cool, so that they, in some measure, acted as a plastic solid mass. The surrounding sediments, of which now a large part is probably eroded, prevented them from breaking out and forming lava flows.

Following the solidification of the intrusive rocks, and marking the close of the igneous episode, there were outpourings of ''mud lavas or tuffaceous breccias.'' These now form the peripheral tuff ring of the Buttes and are composed of ''finely ground up detritus in which lie imbedded angular fragments of andesite, or more rarely rhyolite, of all sizes,'' associated with more or less sedimentary material. Lindgren recognized that ''these mud lavas show a close analogy with similar enormous masses largely covering the flank of the Sierra Nevada,'' and supposed that ''they probably poured out as a semifluid, hot mud, and were only to a less extent the result of ash showers.'' Failing to recognize the presence of a large, central crater in the interior of the Buttes, he presumed that much, if not all, of the tuff and breccia was ejected from lateral vents within the sedimentary ring. Although he did not attempt to describe in detail the mechanics of the intrusion and explosion of the igneous rocks, there is no suggestion that Lindgren believed the volcano to have originated as a laccolith. His map and section indicate the andesitic core to have been punched through the enclosing sediments as a steep-sided, composite stock.

In 1911, Lindgren[6] again summarized the geology of the Marysville Buttes, adding to his earlier account a list of fossils collected from the ''Ione'' beds and identified by Stearns and Dall as of Miocene age. In the same paper, he describes[7] the occurrence of certain tuffs, the Oroville tuffs, along the foothills of the Sierra Nevada, from Bear River to Feather River. These tuffs, which are overlain by Quaternary river gravels, were said to have been deposited on an even slope of the older (Neocene) formations after the ''Ione'' beds had been greatly eroded and after the andesitic eruptions of the adjacent Sierra. Remarking that ''acidic eruptive rocks like those contained in the tuffs are present in the extinct volcano of the Marysville Buttes, which lies in the center of the valley only about twenty-five miles to the southwest or west of these tuff areas,'' Lindgren ''confidently believed that the tuffs represent the accumulations of ash showers from this volcano, especially as the prevailing southwesterly winds would drive them in just this direction.'' Evidence will be cited later suggesting that in this view he was probably in error.

In 1913, Dickerson[8] published an account of the Eocene fauna of the area. In this paper, he redetermined some of the species identified by Cooper for Watts. Cooper, in his later work had suggested that the fossils originally identified by him as ''Cretaceous B'' in age, were probably Eocene. ''The presence of Conrad's 'finger-post of the Eocene' (*Cardita planticosta* Lamarck. . . .) abundantly, at Marysville Buttes, is a strong mark of the Eocene age.'' This conclusion was supported by Dickerson, who followed Lindgren in assigning the fossiliferous beds beneath the ''Ione'' to the Tejon division of the Eocene. Although Hannibal is reported in the paper as having recognized Cretaceous beds in the area south of South Butte, Dickerson accepted the Survey's mapping of that area as Ione. He considered that the fossiliferous Eocene beds of the Buttes were laid down in water about one hundred fathoms deep, under tropical or subtropical conditions, and that they afford no evidence of brackish water or of estuarine deposition. The difference between the Tejon fauna of the type locality and the Eocene fauna at Marysville was considered too great to be due merely to geographic separation, the faunal zone represented at Marysville being regarded as younger than that of the typical Tejon. In 1911, Lindgren had reported "marine Ione (Miocene)" fossils at two localities. On the evidence of further collections at one of these localities and of the lithology at the other, Dickerson asserted "that marine Tejon has been confused with Ione, and that there is no evidence to indicate the presence of an extension of the sea into this region in Miocene time."

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[6] Lindgren, W., The Tertiary gravels of the Sierra Nevada of California. U. S. Geol. Surv., Prof. Paper 73, pp. 119–120, 1911.

[7] *Ibid.*, pp. 26–27, 89–90.

[8] Dickerson, R. E., Fauna of the Eocene at Marysville Buttes, California. Univ. Calif. Publ. Geol., vol. 7, pp. 257–298, 1913.

In 1914, Dickerson[9] subdivided the Tejon formation into four zones, of which the highest was thought to be represented by the Eocene fauna at Marysville. To this topmost zone he applied the term *Siphonalia sutterensis* zone, its most characteristic forms being, in addition to the index fossil, *Phos* (?) *martini* Dickerson and *Drillia ullreyana* Cooper. A littoral fauna, comparable in age with that described from Marysville, was recorded from beneath the Older Basalt of South Table Mountain, near Oroville, both faunas being attributed to a transgressing sea.

Two years later, Dickerson[10] revised his original section at West Butte, Marysville, the lowermost seven hundred feet of which were relegated to the Chico Cretaceous, following the discovery of *Spisula ashburneri* (Gabb), *Trigonia evansana* (Meek), and *Gyrodes expansa* Gabb. The beds which he had assigned to the topmost division of the Tejon were then stated to be the deep-water equivalent of the inshore Ione formation exposed along the foothills of the Sierra Nevada. Especial importance attaches to his recognition of the individuality of a group of beds resting with marked unconformity upon his Tejon and itself succeeded unconformably by the andesite tuffs and breccias that form the peripheral ring of the Buttes. This group he designated the Sutter formation. It is described as being "composed chiefly of rhyolitic ash, rhyolitic tuff-breccia, thin flows of rhyolite and conglomerate containing rhyolitic and quartz pebbles."

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[9] Dickerson, R. E., Note on the faunal zones of the Tejon group. Univ. Calif. Publ. Geol., vol. 8, pp. 17–25, 1914.

[10] Dickerson, R. E., Stratigraphy and fauna of the Tejon Eocene of California. Univ. Calif. Publ. Geol., vol. 9, pp. 403–406, 1916.

These materials were erroneously supposed to have been derived chiefly from the rhyolitic necks which Lindgren had properly regarded as intrusive into the andesites. Evidence will be offered later to show that the Sutter beds are essentially the detrital equivalents of the Tertiary rhyolitic and andesitic deposits of the Sierra Nevada and that the rhyolitic necks were intruded into and deformed them. In a brief discussion of the historical geology of the Buttes, Dickerson controverts much of the interpretation presented by Lindgren. He supposed that the intrusion of the rhyolites was instrumental in upturning and faulting the Eocene and Cretaceous strata prior to the intrusion of the andesites, and that there were eruptions of rhyolitic flows and ash from these local necks, forming the Sutter beds. It will be argued subsequently that in these views he was in error, that the deposition of the Sutter formation preceded the intrusion of both the andesites and rhyolites of the Buttes, and that at no time did lava flows issue from local vents.

In 1918, Clark[11] affirmed the individuality of the Meganos or middle group of the Eocene formation, separated by unconformities from both the Tejon group above and the Martinez group below. To this newly established Meganos group, he referred the *Siphonalia sutterensis* zone which Dickerson had described from the Marysville Buttes as the topmost division of the Eocene. Clark carefully ''refrained from using the name Ione for the beds belonging to this epoch of deposition,'' believing ''that the Ione very probably is composed of beds belonging to more than one epoch of deposition.'' In a subsequent paper,[12] he definitely correlated the Meganos group with the marine Ione of the Sierran foothills, as mapped by Lindgren and Turner, though not with the Ione of the type section. In this paper, also, the general faunal relationships of the Meganos group, including its representatives at Marysville, are fully discussed.

Finally, in 1926, Stipp[13] described a foraminiferal assemblage from the glauconitic Meganos beds of the Marysville Buttes. He states that the assemblage is marked by the occurrence of one pelagic species, several bottom-dwelling, cold-water species, and several warm-water species. ''A species of *Orthophragmina* is present and its occurrence in this latitude (39° 12′ N) is believed to be the most northern on record.'' Most of the species are of long geological range and 60 per cent are Recent. He agreed with Dickerson in the belief that the beds were laid down in water about one hundred fathoms deep, at or near the edge of a continental shelf, with open-sea conditions prevailing. Further details of Stipp's work will be included in the sequel.

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[11] Clark, B. L., The Meganos group, a newly recognized division in the Eocene of California. Bull. Geol. Soc. Am., vol. 29, pp. 281–296, 1918.

[12] Clark, B. L., The stratigraphic and faunal relationships of the Meganos group, Middle Eocene of California. Jour. Geol., vol. 29, pp. 130–131, 1921.

[13] Stipp, T. F., The Eocene foraminifera of the Marysville Buttes. Thesis submitted for the degree of M.A. at Leland Stanford, Jr., University, 1926.

STRATIGRAPHIC SUCCESSION AND SUMMARY OF EVENTS

The general succession at the Marysville Buttes is as follows:

	THICKNESS IN FEET
8. Andesite tuff and breccia	Up to 600
7. Intrusive rhyolite porphyries and minor pyroclastic deposits.	
6. Intrusive andesite porphyries.	
5. *Sutter beds* (?Middle Neocene): predominantly rhyolite tuffs below and pyroxene andesite tuffs above, admixed with sediments	500—1000+
4. *Butte gravels* (Middle Eocene, Meganos): coarse gravels composed of rounded, chiefly siliceous pebbles, with sandy intercalations and thin beds of massive sandstone and siliceous limestone. Minor disconformity	450—1200
3. *White Ione sands* (Middle Eocene, Meganos): siliceous sands with anauxite; often stained brown, pink, or purple. Minor disconformity	100— 150
2. *Marysville formation* (Middle Eocene, Meganos): buff sands and sandstones with ferruginous and calcareous concretions and glauconitic shales. Disconformity	300— 600
1. *Chico beds* (Cretaceous): brown-weathering, gray-green sandstones with interbedded conglomerates, gray limestones, and gray-black shales. Base unknown	1560+
Total thickness of beds	3510—5110

The general sequence of events which gave rise to the above succession may be enumerated briefly as follows:

a. An extensive transgression of the Cretaceous sea from the west.

b. Elevation and planation of part of the Cretaceous beds during the lower Eocene (Martinez) period.

c. Renewed submergence permitting, first, the deposition of fresh or brackish water, pebbly grits, and subsequently of fossiliferous middle Eocene sands and shales, locally rich in glauconite.

d. A possible slight elevation and resultant erosion, accompanied by the formation of the white Ione sands, perhaps as inshore deposits and alluvial and deltaic fans.

e. A period of intense erosion in the Sierra Nevada, when the larger rivers carried their loads into the Sacramento Valley to form the Butte gravels.

f. Rhyolitic and andesitic eruptions in the Sierra Nevada, separated by periods of erosion and aggradation, beginning, perhaps, in the Oligocene or Miocene and continuing during the ''Middle Neocene'' (Upper Miocene to Lower

Pliocene): denudation and re-deposition of these volcanic rocks and of the associated gravels both during and after the volcanic episode, producing the Sutter formation in the shallow water of the Sacramento Valley, on a floor that was gently subsiding.

g. The aggressive intrusion of a ''steep-dome laccolith'' of andesite porphyry during the middle or late Pliocene period, upturning the adjacent sediments and producing in them a plexus of faults, disposed both radially and concentrically with respect to the laccolithic margins.

h. Erosion of the sedimentary cover from the top and sides of the laccolith down to a level almost identical with that of the sediments as now exposed.

i. Intrusion of rhyolitic necks or domes into both the andesites and the upturned sediments, folding the latter still farther, accompanied by minor eruptions.

j. Continued erosion resulting in the formation of deep valleys among the sediments on the flanks of the laccolith, particularly along the radial fault lines.

k. A series of violent steam explosions, chiefly from a central crater in the core of the laccolith, involving the comminution and ejection of masses of solid andesite and rhyolite as tuff and breccia.

l. Erosion and removal of much of the andesite tuff and breccia so as to expose what is almost the pre-eruption surface of the sedimentary hills.

DETAILED DESCRIPTION OF THE SEDIMENTARY SUCCESSION

Introductory Remarks

The andesitic core of the Marysville Buttes is almost entirely surrounded by a ring of sediments which reaches a maximum width of almost two miles and is itself enclosed by an outer ring of andesite tuff and breccia (fig. 2 and map). This ring of sediments, by reason of its comparative softness, forms a belt of relatively low relief that rises inwards gently but evenly to the steep-sided core of andesite. Its topographic individuality is very impressive. On a large scale, the ring resembles somewhat the encircling fossa of an ancient citadel, overlooked by an outer rampart, here represented by the peripheral revet-hills of andesite tuff. The topographic unity of this sedimentary ring is the more sharply defined by the gently molded forms of its constituent hills, in contrast with the long and regular slopes of the outer tuff ring and the high, serried peaks of the andesitic core (fig. 3).

In their most typical development, along the southern base of South Butte, these low, rounded hills of sedimentary rock are concentrically disposed about the laccolith, and recall the ''revet-crags'' associated with the laccoliths of the Henry Mountains, Utah, so vividly described by Gilbert.[14] Elsewhere, they are irregularly traversed by narrow stream channels or are unequally domed by intrusions of rhyolite.

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[14] Gilbert, G. K., Report on the geology of Henry Mountains. U. S. Geog. and Geol. Surv. of the Rocky Mountain Region, pp. 26 *et seq.*, 1880.

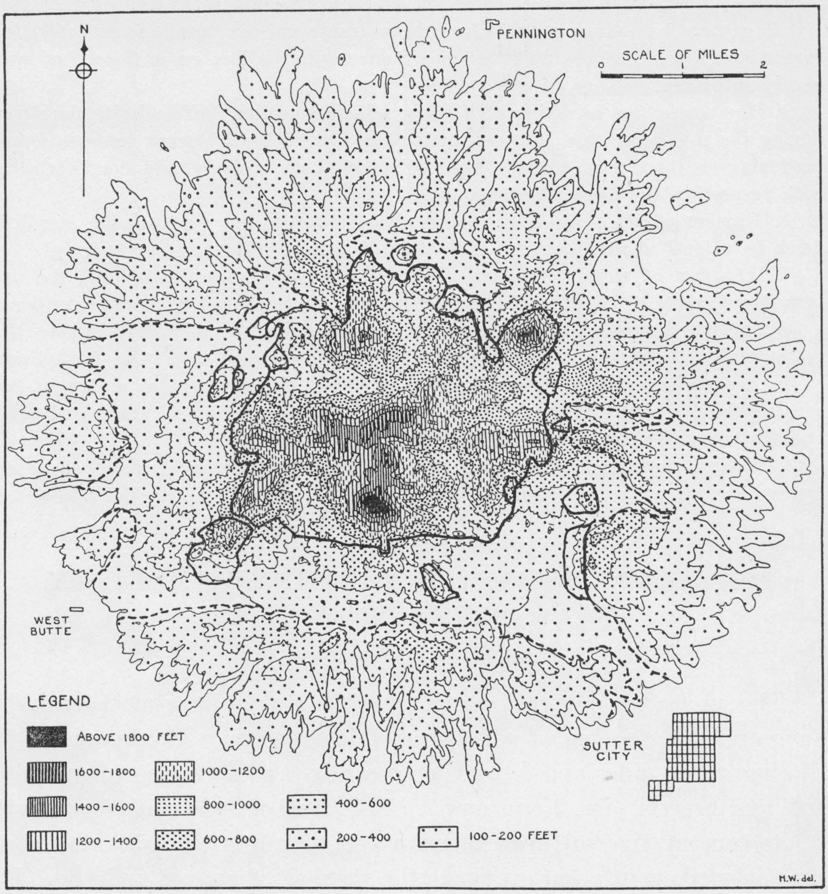

Fig. 2. Illustrating the relation between the topography and the geology of the Marysville Buttes. The andesitic laccolith and rhyolitic intrusions are enclosed by heavy lines; the sedimentary "ring" lies between the heavy lines and the broken lines, and the peripheral andesite breccias lie outside the broken lines.

The intrusion of the andesite broke the sediments into large blocks separated from each other by radial faults. The resultant sectors were then tilted outwards from the laccolith at various angles so that the lowermost sediments are now exposed on the inner side of the steepest blocks, whereas in the less steeply tilted blocks only the topmost or Sutter beds are revealed.

The identification of horizons in the sediments of the Marysville Buttes is frequently a matter of difficulty. Except in restricted bands, such as the glauconitic shale-bands of the Meganos group or in the higher sandstones of the Chico series, fossils are rare. There is, moreover, a bewildering repetition of certain lithological types at widely separated horizons. This repetition appears to be due in part to frequent reworking of the sediments, but arises chiefly from the recurrence of similar conditions of deposition. Particularly confusing are the lenticular masses of ferruginous, buff sandstones that occur at several horizons in the Chico and lower Meganos groups and reappear locally among the Butte gravels. Sharp contacts between the various formations are exceptional; thus, where the basal layer of white rhyolite tuff is absent from the base of the Sutter formation, it is sometimes difficult to determine upon a precise line of contact with the sandier, upper members of the Butte formation. A similar difficulty thwarts any attempt to determine the exact junction of the Chico with the overlying Eocene. In view of these conditions, it is extremely doubtful if mechanical analysis of the sediments would be of material assistance except in a few particular cases.

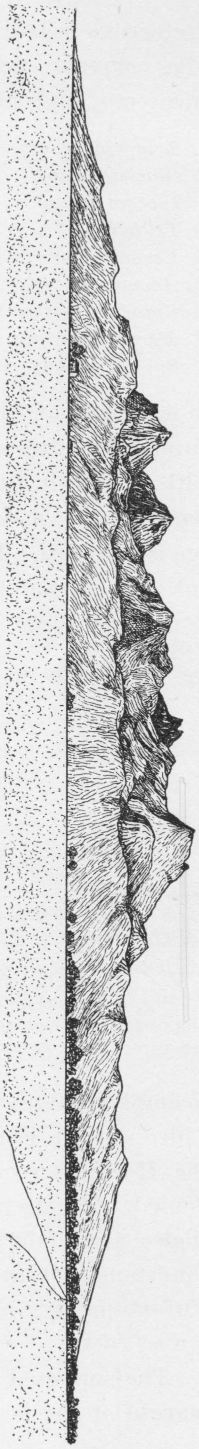

Fig. 3. View of the Marysville Buttes from near Williams, twenty miles to the west. South Butte is the high peak on the right; West Butte is the central peak.

CRETACEOUS BEDS

The lowermost beds are exposed along and near the southern and western margins of the laccolith, and are also revealed along the flanks of the prominent rhyolitic intrusion near the hamlet of West Butte (see map). The latter intrusion is almost completely enclosed by sediments of Cretaceous age. On its western side, a fairly complete dip-section is revealed across the Cretaceous and Tertiary beds (fig. 4). Hereabouts, the difference of dip between these beds is hardly appreciable, but a thin pebbly grit-band, carrying shallow- and brackish-water fossils, provides an easily recognizable local base to the Eocene. The

Cretaceous beds dip westward at 40° to 50°. The uppermost member is a compact, pale brown-weathering, gray-green sandstone, often micaceous, and carries a fauna including:

Trigonia evansana (Meek)
Glycimeris sp.
Inoceramus sp.
Tellina sp.
Venericardia (large)
Amauropsis sp.
Gyrodes expansa Gabb
Meretrix varians Gabb
Spisula ashburneri (Gabb)

It is clearly of Chico age. The sandstone is underlain by from four hundred to five hundred feet of a crumbly, gray-black shale, often with a bluish tinge. Except for abundant though minute plant remains, the shale is apparently unfossiliferous, so that its precise age is doubtful. The great thickness of the Chico formation in regions not very distant from the Marysville Buttes may, however, be taken to imply that the gray-black shales at Marysville also belong to the Chico series. For the present, the possibility of their equivalence to the Horsetown or Knoxville (Lower Cretaceous) shales cannot be denied. Finally, close to the margin of the rhyolite porphyry, the shales are underlain by buff and brown-weathering, concretionary sandstones not unlike the topmost Chico sandstones already mentioned. Unfortunately, no fossils have as yet been recovered from these lowest rocks.

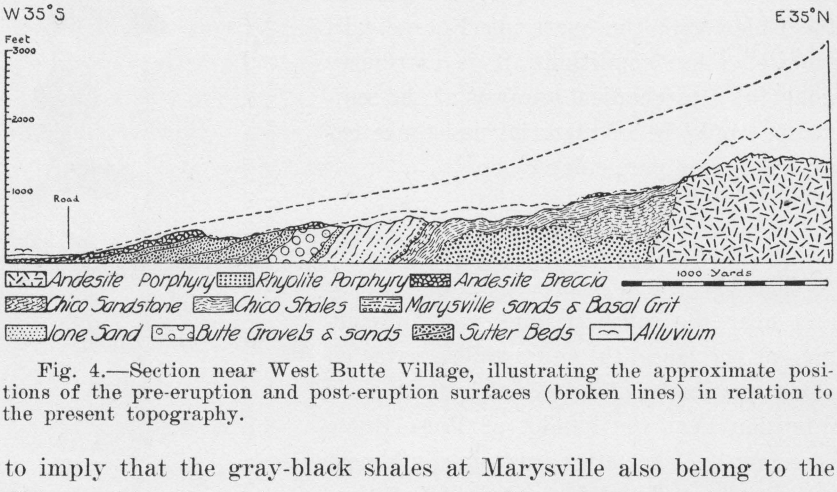

Fig. 4.—Section near West Butte Village, illustrating the approximate positions of the pre-eruption and post-eruption surfaces (broken lines) in relation to the present topography.

The supposed Chico shales again outcrop within a few feet of the margin of the laccolith to the northwest of the above section, on the western face of "1657 Hill" (map) and are widely exposed on the southern face of South Butte. At these localities, they have suffered contact metamorphism, so that their gray-black color is replaced by a pale bluish gray tint. In addition, the shales are indurated and brittle, and the sandier, brownish intercalations exhibit a notable bleaching. Considering the mass of andesite and the proximity of the shales to the contact, however, the degree of metamorphism is surprisingly small.

Not only are the Chico beds revealed adjacent to the laccolith near West Butte, but they are repeated at a distance of half a mile therefrom by a fault that runs almost parallel to the laccolithic margin. The exact nature and thickness of the Cretaceous beds thus repeated is uncertain owing to the paucity of exposures; the beds appear to be chiefly buff sands and gray shales, without any conspicuous layers of standstone, and are deeply weathered.

In his east-west section through the sediments near West Butte, Dickerson describes [15] the occurrence of seven hundred feet of Chico beds containing in their upper hundred feet *Spisula ashburneri* (Gabb), *Trigonia evansana* (Meek), and *Gyrodes expansa* Gabb. These hundred feet of "impure gray limestone with thin strata of hard gray, medium-grained sandstone" are said to overlie "600 feet of massive, medium-grained, yellow, non-fossiliferous sandstone in contact with the andesitic core." The writer has been unable to identify this succession.

The fullest development of the Cretaceous rocks occurs in the highly inclined block immediately to the south of South Butte, and consists of an irregular alternation of sandstones, limestones, and conglomerates overlying the baked shales already mentioned. A typical north-south dip-section reveals the following sequence in ascending order (fig. 5).

	THICKNESS IN FEET
1. Baked, gray-blue shales	400+
2. Brown-weathering, ferruginous gray sandstone	30
3. Pebbly conglomerate with black chert and brown mudstone pellets; fossiliferous	80
4. Concretionary, ferruginous buff sandstone	10
5. Brown mudstone and sandy gray limestone	20
6. Gray-green sandstones with pebbles of chert and micaceous mudstone	30
7. Gray-green, micaceous sandstones, locally concretionary	250
8. Sandy limestones with occasional cone-in-cone structures and mud cracks	20

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[15] Dickerson, R. E., *op cit.* (note 10), p. 404, 1916.

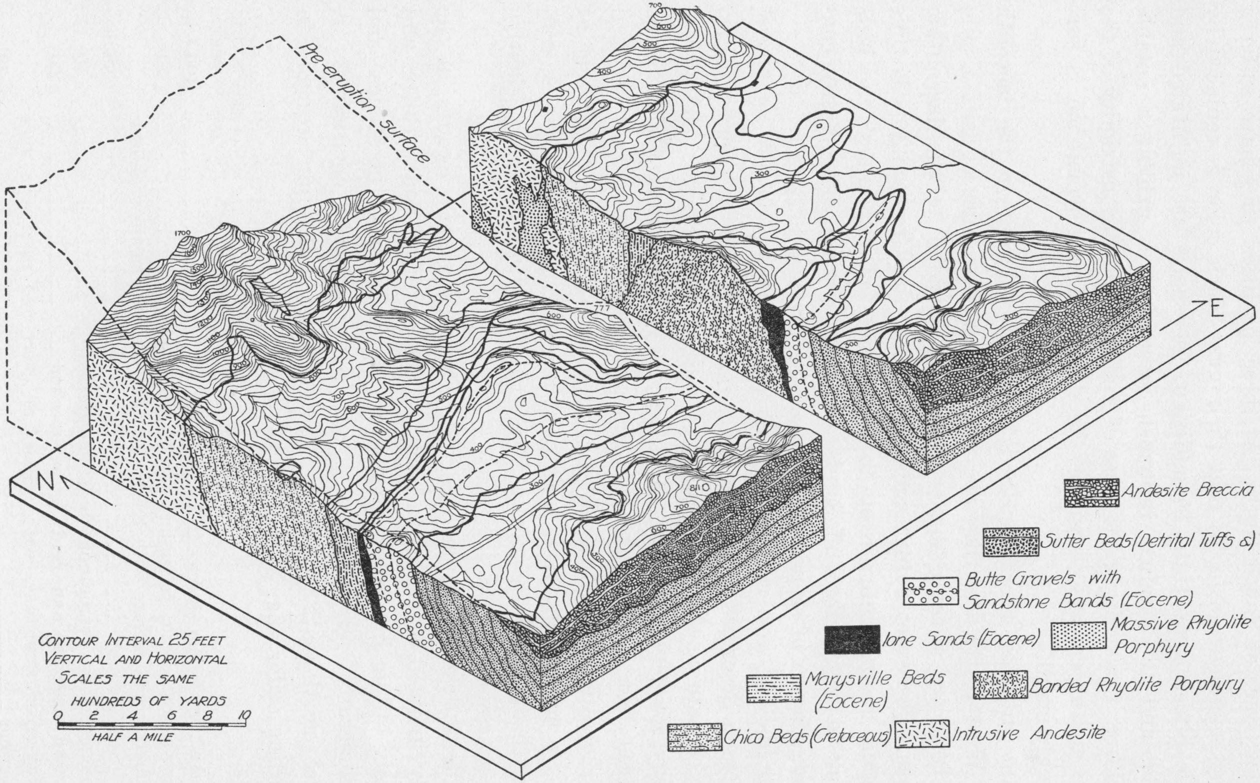

Fig. 5. Block diagram illustrating the succession and structure of the sediments adjacent to the southern margin of the laccolith near South Butte

9. Brown-weathering, flaggy, gray limestone with sandy intercalations	100
10. Gray limestone	30
11. Blocky, calcareous, gray mudstone	60
12. Gray, compact mudstone	30
13. Brown-weathering, gray-green sandstone	50
14. Blue-gray, concretionary, calcareous mudstone	50
15. Brown-weathering, gray-green mudstone and sandstone and buff, concretionary sands	400+
Total thickness	1560+

The exact location of the Eocene-Cretaceous contact in the sedimentary block south of South Butte has not been satisfactorily determined; thereabouts, the limited exposures suggest that near the contact the rocks are of uniform lithology, concretionary, buff sands predominating. It is clear, however, that if there be an angular unconformity between the two series, it is slight.

About two hundred feet below the contact, the Chico series includes two impersistent bands of conglomerate, each some six feet thick. These bands are separated by six feet of ferruginous, highly concretionary sands, in which ovoid concretions reach about a foot in length. Similar sands occur both above and below the conglomerates. A disconformity occurs at the base of the lower conglomerate: at one locality, within the space of ten yards, the conglomerate is seen to transgress the underlying sands to a depth of six feet, and obviously lies on an irregular surface. Traced along their strike, both conglomerates rapidly disappear. They are chiefly composed of flat slabs of the underlying sandstones, together with siliceous pebbles (especially milky quartz and black chert), in a sandy matrix. Some of the sandstone slabs are as much as two feet in length, though not more than six inches thick; most of them are from two to six inches long and an inch or so in thickness. Their forms suggest a nearby source, possibly a talus or beach débris derived from cliffs of flaggy sandstone. The sandy matrix is extremely rich in fragmentary fossils, particularly of *Ostrea*. Large forms of *Glycimeris veatchii* Gabb and *Trigonia evansana* (Meek), and less commonly of *Exogyra parasitica* Gabb, may also be found. The extent and degree of disconformity beneath the conglomerates cannot be large; there appears to be no adequate reason to suppose that one is dealing here with more than a slight and local oscillation of a Chico shore line. The conditions of deposition which followed the formation of the conglomerates must have been similar to those which had obtained previously; where the conglomerates disappear along the strike, there appears to be an uninterrupted succession of buff sands along the same horizon.

The topmost sandstones of the Chico series in the sedimentary block south of South Butte are often highly fossiliferous, but the fauna is notably restricted in the number of its species. These sandstones outcrop at intervals over an east-west distance of two and a half miles, but the best fossil locality is on the hillock, one-quarter mile south of Moore's ranch, three miles northwest of Sutter City. Here may be obtained:

Tellina matthewsoni Gabb
T. nanaimoensis Gabb
T. ?hoffmanniana Gabb
? *Meretrix lens* Gabb
Lucina dubia Gabb
Acila truncata Gabb
Dentalium stramineum Gabb
Sharks' teeth and plant remains.

Fully 80 per cent of the fauna is made up of large forms of *Tellina matthewsoni*, and gastropods appear to be absent. The lithology of these topmost Chico sandstones resembles that of some of the Chico sandstones at Pentz, near Oroville, and along the foothills of the Coast Ranges, west of Colusa.

Eocene Beds

The Marysville Buttes may have been an area of non-deposition during lower Eocene time, for the fauna recovered from immediately above the Cretaceous is believed to be of Meganos age (middle Eocene). It is impossible to assess the amount of erosion to which the Chico was subjected during this pre-Meganos interval, but the absence of any notable difference of dip between the Chico and the Eocene suggests that hereabouts the interval was not marked by any conspicuous folding. On the evidence of fossils, it seems that only the Meganos division of the Eocene is present at Marysville; on the evidence of lithology, to be cited hereafter, there is reason to refer the succeeding beds—the Sutter tuffs—to the Miocene and Pliocene. The formation of the supposed Meganos beds appears, therefore, to have been preceded and followed by long intervals of non-deposition. The Meganos beds themselves are also interrupted by minor disconformities and include types that differ markedly in lithology. Indeed, on lithological grounds, the beds fall naturally into three groups, the Marysville formation below, the Ione sands in the middle, and the Butte gravels at the top.

THE MARYSVILLE FORMATION

This group consists essentially of loose, buff sands, usually traversed by parallel strings of ferruginous concretions and by thin, lenticular masses of compact, green-gray sandstone and, more rarely, of limestone. In many places, this sandy suite is associated with a thick development of green-gray, glauconitic shales that weather to a deep reddish brown soil. The lithology and thickness of the Marysville beds are, however, extremely variable over small areas. In some places (e.g., section, fig. 4), on the western side of the Buttes, the lowermost horizon consists of a pebbly grit, rich in well rounded fragments of black chert and quartz, and carries a species of *Melania*, indicative of shallow- or brackish-water conditions. It seems that here, at least, the Eocene sea transgressed onto a floor that was almost flat. Above the *Melania*-bearing grit, lie three hundred feet of buff sands with many beds of sandstone, mostly from three to six feet thick, and lines of ovoid concretions. In this section no shales are exposed. A similar succession of the Marysville beds is developed throughout the area south of South Butte. Thick, massive beds of hard sandstone, such as typify the Chico series, are absent. The Marysville beds are characterized, rather, by the abundance of ferruginous concretions, which range in size from that of a hen's egg to four or even five feet long and frequently weather out of the friable sands as strings of nodules.

A quite different section of the Marysville beds is that exposed in "Fig Tree Gulch," a narrow, east-west valley, about two and three-quarters miles west of the summit of south Butte. At this locality, the white Ione sands are underlain by "100 feet of green-gray sandstone and shale with limestone concretions," and these by "300 feet of green-gray, glauconitic shale."[16] Below the latter, follows a very poorly exposed and deeply weathered series of buff sands and shales of unknown thickness. This series may include Chico beds, as indicated on the map.

The rich fauna described by Dickerson as Tejon, and the faunas recorded earlier by Watts and Lindgren, were collected from the green-gray beds immediately beneath the white Ione sands. It is unnecessary to describe the characters of the fauna in this place. Clark[17] believes that it belongs to the Meganos group, and not to the topmost Tejon (Eocene) as Dickerson supposed. The excellent preservation of the fossils, particularly in the partly weathered nodules among the glauconitic shales, invites further collections, and it is likely that a still richer fauna than that heretofore recognized may yet be obtained. Fossiliferous, glauconitic muds were traversed in a well, drilled for oil, about three-quarters of a mile southwest of Fig Tree Gulch. All the species therefrom occur in Dickerson's faunal list. The fossils were said to have been obtained at a depth of 2000 feet, but, unfortunately, little reliance can be placed on this estimate.

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[16] Dickerson, R. E., *op cit.* (note 8), p. 261, 1913.

[17] Clark, B. L., *op cit.* (note 11), 1918.

The glauconitic shales and underlying clay shales of Fig Tree Gulch were examined microscopically by Stipp[18] He found the former to "consist of rounded grains of glauconite, and also of clay, quartz and tests of minute mollusca, bryozoa, corals, ostracods and foraminifera," and concluded, as Dickerson had, that they were deposited at a depth of approximately one hundred fathoms in warm waters. The list of foraminifera identified by Stipp is as follows:

Anomalina grosserugosa (Gümbel)
Cristellaria dickersoni Stipp
C. hannai Stipp
C. rotulata (Lamarck)
Discorbis allomorphinoides (Reuss)
D. ventricosa (H. B. Brady)
Globigerina bulloides d'Orbigny
Lagena marysvillensis Stipp
Nodosaria micronata (Neugeboren)
N. raphana (Linnaeus)
Orthophragmina cf. *clarki* Cushman
Pulvinulina helicella Hanna
P. karsteni (Reuss)
P. schenki Stipp
Quinqueloculina stevensi Stipp
Rotalia soldanii d'Orbigny
Siphonina reticulata (Czjzek)
Textularia sp.
Truncatulina wuellerstorfi (Schwager)
Verneuilina israelskyi Stipp
Arenaceous species from the buff-colored clay shales underlying the glauconitic shales.

Most of the above species, according to Stipp, are unattached bottom-dwellers. He observed that "no arenaceous species except of the genera *Textularia* and *Verneuilina* were found in the glauconitic foraminiferal shales of the Marysville Buttes, but in the underlying, buff-colored clay shales several species of arenaceous foraminifera, but no calcareous species were found.'' *Orthophragmina clarki* Cushman had previously been described from the Coalinga district,[19] from beds included in the Meganos of Clark. Concerning his find of a closely similar species at Marysville, Stipp writes: ''The genus *Orthophragmina* which is confined to the Eocene is known as a shallow water foraminifer of tropical regions, and its occurrence in a fauna composed chiefly of deeper water species, and at this latitude, 39° 12′ N, is noteworthy.'' The general appearance of the foraminiferal assemblage at Marysville is considered by others[20] to be strikingly like that of certain Eocene shales exposed along the Cowlitz River, Washington.

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[18] Stipp, T. F., *op. cit.*, 1926.

Green, glauconitic shales similar to those found in Fig Tree Gulch outcrop near the margins of the laccolith, by Keenan's Ranch, two and a half miles east of Noyesburg School. Viewed under the microscope, these shales also are seen to contain bryozoan remains, associated with species of *Cristellaria, Nodosaria, Pulvinulina,* and possibly of *Orthophragmina.*

On the north side of the Buttes, three miles south of Pennington, a trial hole for coal revealed dark gray mudstones, rich in carbonaceous matter, close to the side of the laccolith. Unfortunately, the precise attitude of these beds is unknown, so that their correlation with the Marysville formation is not conclusive. Half a mile to the southwest of this locality, a small series of exposures of dark gray mudstone and greenish gray siltstone occurs in association with intrusive rhyolites and andesites. It is believed, on lithological grounds, that these beds almost certainly belong to the Marysville formation and represent the only remnants of the sedimentary sheet which once covered most, if not all, of the andesitic laccolith. Their relations to the igneous rocks will be discussed at a later stage.

On the east side of the Buttes, the Marysville beds are widely exposed in a broad, southward-pitching anticline. They are predominantly buff, concretionary sands that carry a few thin seams of an inferior coal, interbedded with gray and gray-green shales, the latter being glauconitic. From these shales and from the associated lenses and nodules of limestone, both Lindgren and Dickerson obtained an abundant fauna. Lindgren believed the fauna to be of Miocene age; Dickerson assigned it to the topmost division of the

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[19] Cushman, J. A., U. S. Geol. Surv., Prof. Paper 125, p. 41, 1920.

[20] Hanna, G. D. and Hanna, M. A., Foraminifera from the Eocene of Cowlitz River, Lewis County, Washington. Univ. Wash. Publ. Geol., vol. 1, p. 58, 1924.

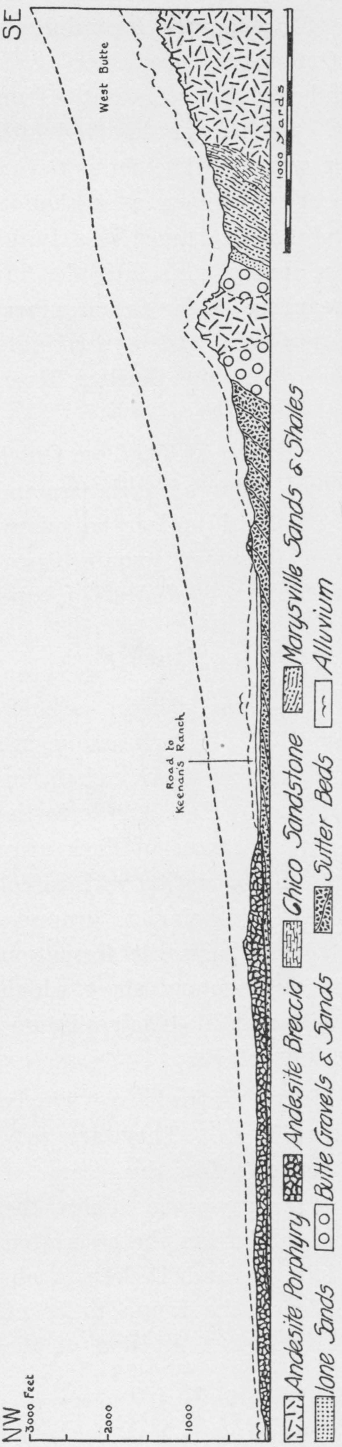

Fig. 6. Section across the northwest side of the Buttes; the broken lines indicate the approximate forms of the pre-eruption and post-eruption surfaces.

Tejon (Upper Eocene); Clark, whose determinations are followed here, refers it to the Meganos group of the Eocene.

The general appearance of the Marysville formation is suggestive of deposition in water of moderate depth. Although the presence of glauconite cannot be regarded as a safe criterion in any estimate, the character of the fauna, as Dickerson has shown, is indicative of deposition at a depth of about one hundred fathoms. The occurrence of plant remains and of coal seams at many horizons is also suggestive of shallow-water conditions.

THE IONE SANDS[21]

The Marysville formation is succeeded by a thin development of sand, of remarkable and constant lithology. This sand is especially conspicuous by reason of the fact that it is usually pure white, or is irregularly streaked in shades of pink, purple, or brown by the oxidation of small amounts of iron. It is no less unique by reason of its abnormally high content of quartz and the presence of a bleached, white hydro-mica, anauxite.

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[21] I am indebted to Dr. V. T. Allen for his kindness in permitting this brief, advance statement of his work, and have benefited greatly by his wide experience of the Ione sediments of the Sierran foothills.

Owing to its incoherence, the sand weathers readily, giving rise locally to long, narrow strike-valleys, as along the northern slopes of West Butte Pass (pl. 12*b*). Except where it is traversed by deep stream channels, the sand is rarely exposed. So distinctive are these limited outcrops, however, that their distribution affords a valuable clue to the geological structure in many areas where otherwise mapping would be extremely difficult.

The term Ione has been applied to these sands in the sense adopted by Allen. Previous to Allen's work, the term had been used so widely to include deposits of very different lithology and often of different ages, that it had long since lost all accurate connotation. It is unnecessary to discuss the former usage of the term in this place, since the reader may find a complete discussion thereof by Allen. Allen has redefined the term, restricting it to the quartz-anauxite sands of the Meganos. His work indicates clearly that this peculiar lithological unit is of surprising uniformity throughout a wide belt along the foothills of the Sierra Nevada, and that it probably represents a single, persistent horizon. He has shown, moreover, that the Ione sands are probably the age-equivalents of the "Bench gravels" of the Sierra, and that they were chiefly derived by the erosion of an intensely weathered granitic series.

There can be no question that the white Meganos sands of the Marysville Buttes had a provenance in the Sierra Nevada. Allen's microscopical studies of the deposit have shown that it carries certain minerals pointing conclusively to derivation from the metamorphic "Bedrock series" of that region.

The thickness of the Ione group at Marysville varies between about one hundred and one hundred and fifty feet, although there is nowhere a complete section. Its contact with the Marysville formation has not been seen, but the lithological change appears to take place rapidly. As Allen has pointed out, the rapid disappearance of biotite and the equally rapid development of anauxite suggest a radical change both in the conditions of deposition and in the sources of the material. That no long period of time elapsed between the deposition of the Marysville and Ione beds is clear from the fact that both, together with the thick, overlying Butte gravels, appear to belong to the Meganos division of the Eocene. It would be difficult, however, to account for so sudden a lithological change on the hypothesis that sedimentation was continuous. The Butte gravels occasionally rest unconformably upon the Ione sands: thus, south of South Butte, the former dip 65° S, whereas the latter dip at 50°–55° in the same direction. Again, on the east side of the Buttes, the gravels rest on a pitted, uneven surface of the sands (pl. 11*a*). At other localities, the sands grade into the Butte gravels, so that the limits of the groups are quite arbitrary. The upper part of the Ione in such cases is itself gravelly; otherwise it merely differs from the typical sand in the presence of brown and green biotite. It is likely, therefore, that the disconformities are of local character. Moreover, the Ione is often characterized by strong current-bedding and must represent a shallow-water deposit. It may have been formed as a series of deltas; the irregular thickness of the group and the local disconformities at its top may thus be explained.

Both the Butte gravels and the Ione sands are remarkably siliceous. This, indeed, is by far their most striking character. The Ione sands, however, are especially rich in grains of glassy and milky vein-quartz, which may constitute as much as 95 per cent by volume of many specimens. With the quartz grains are many rounded pebbles of black chert. In the overlying Butte gravels, the proportion of milky quartz grains gradually diminishes, their place being taken by other siliceous materials, such as quartz porphyries, variegated cherts, schists, and hornfels.

THE BUTTE GRAVELS

A series of gravels with interbedded, loose sands and thin lenses of limestone and sandstone overlies the delta sands of the Ione formation. These gravels almost everywhere give rise to low, rounded hills (pl. 9*b*) and to very distinctive soils heavily charged with pebbles. Concerning these gravels, Lindgren wrote:[22]

> Among the Neocene beds of the Marysville Buttes there are gravels of varying degrees of coarseness, some of the pebbles being 5 inches or more in diameter. All of the pebbles are well washed, and consist of quartz, siliceous sedimentary rock, diabase, granite, and serpentine. All of this gravel . . . . [is] slightly auriferous. . . . . The gold is well rounded and, as a rule, is moderately fine. A few exceptionally large pieces, up to a value of five dollars, are reported to have been found. In some places these deposits might be profitably washed by the hydraulic process if it were possible to obtain sufficient water. These coarse auriferous gravels are certainly a most interesting feature, occurring as they do so far removed from their source in the Sierra Nevada. There are no indications of quartz veins in the buttes.

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[22] Lindgren, W., U. S. Geol. Surv., Marysville Folio, no. 17, 1895.

The Butte gravels are rarely well exposed. Their thickest development occurs along West Butte Pass where the beds dip steeply to the south or stand vertically and have a maximum thickness of about 1200 feet (pl. 9*b*). Here they consist essentially of gravels, often current-bedded, with thin seams of laminated, ferruginous clays and sands, and two conspicuous hard beds each about 4 feet thick, one a gray limestone and sandstone, 150 feet above the Ione formation, and the other a brown-weathering, fossiliferous sandstone, 700 feet above the Ione. The latter sandstone carries a fauna that Clark believes to be of Meganos (Eocene) age. Its most abundant form is *Turritella merriami* Dickerson, which occurs in great clusters, the individual specimens being of large size. The list of fossils thus far recovered from this sandstone is as follows:

Turritella merriami Dickerson
Ficopsis meganosensis Clark and Woodford
Chrysodomus ? martini Dickerson
Turbinella marshensis Clark and Woodford
Siphonalia sutterensis Dickerson
Calyptraea sp.
Tellina aff. *remondii* Gabb
Modiolus ornatus Gabb
Leda aff. *gabbi* Conrad
Pteria sp.
Cardium marysvillensis Dickerson
Cardium cooperi Gabb
Venericardia sp.
Worm tubes.
Plant remains

On the southeast flank of the laccolith, near Kellog's Ranch, the Butte gravels rest on an eroded and pitted surface of the Ione sands (pl. 11*a*). The pebbles in the basal gravels usually lie flat. They are well rounded and almost wholly siliceous, the principal types being, in the order of their importance: flinty, gray and gray-green porphyritic rhyolite (rhyolite porphyry or quartz porphyry) derived from the 'Bedrock Complex' of the Sierra; milky quartz; gray, blue-black, and purple chert; "greenstone"; fine, gray and pink granodiorite; banded siliceous schist; dark gray, compact mudstone; pebbly quartz grit; dark gray andesite and dense basalt; blood-red chert; glassy quartz. This assemblage resembles fairly closely that of the "auriferous gravels" immediately beneath the Tertiary volcanic deposits along the course of the "Neocene Yuba River," as at Smartsville. There can be no doubt, indeed, that most, if not all of the pebbles were derived from the Sierra Nevada. It is true that among the pre-volcanic ''auriferous gravels'' on the slope of the Sierra, the proportion of ''greenstone'' pebbles is much greater than it is among the Butte gravels at Marysville, but this is only to be expected, for with increasing distance from the source, the less resistant ''greenstones'' would gradually diminish in amount while the more siliceous pebbles would show a relative increase. Some of the materials of the gravels may well have been derived from a source toward the northeast.

It is probable that the Butte gravels represent an alternation of shallow-water marine deposits with fluviatile and delta accumulations. The remarkably rapid variations in the lithology and thickness of the Butte gravels, the lenticular character of the sandstone members, the abundance of shallow-water marine fossils and of plant remains, the presence of current-bedding, these and other phenomena lend support to this idea. Allen has suggested that the Butte gravels may be, in part, beach deposits due to the re-working of the ''Bench'' and ''Deep Gravels'' of the Sierra as a result of a movement of the Sierra immediately before the period of Tertiary volcanic activity. In this way much of the ''Bench'' and ''Deep Gravels'' may have been stripped from the present site of the Sierran foothills and been transported westward into the Sacramento Valley. It is interesting to observe, in this connection, that a deep boring recently made at the town of Marysville, midway between the Marysville Buttes and the Sierran foothills, failed to reveal any coarse gravels that might correspond to the Butte gravels immediately beneath the Tertiary rhyolites and andesites. At the Marysville Buttes, the Butte gravels are immediately overlain by rhyolite tuffs; at the Marysville boring, the rhyolite tuffs overlie about three hundred feet of blue and brown clay. The age of these clays is unknown, but they may be equivalent to the Marysville formation, in which case it would seem that the Ione sands and Butte gravels had been eroded prior to the period of rhyolitic eruptions.

The nature of the pebbles in the Butte gravels makes it certain that they were derived from the same source as the pre-volcanic ''auriferous gravels'' of the Sierra; for the present, however, the question as to whether or not the Butte gravels are merely re-worked ''auriferous gravels'' must remain unanswered.

On the west side of the Marysville Buttes, the formation has an average thickness of about six hundred feet, the gravels are finer and are associated with a larger development of sands. Here again the

Sierran provenance of most of the material cannot be doubted, but there is a possibility that much of the sandy admixture may have been derived from the Coast Ranges to the west, by the erosion of part of the Chico sandstones. No coarse siliceous gravels of Eocene age appear to exist in this part of the Coast Ranges, nor is there any apparent source in that direction for the siliceous pebbles of the Butte gravels.

Summary.—The Meganos (Eocene) beds at the Marysville Buttes thus include three distinct divisions—the Marysville formation, the Ione sands, and the Butte gravels—separated by minor, local disconformities and must represent a long period of time during which the conditions of deposition underwent radical changes. Most of these beds, as well as the overlying Sutter formation, were derived from sources in the Sierra Nevada and can be correlated with beds now occurring in the Sierran foothills. Unfortunately, we know nothing, as yet, concerning the conditions that obtained in the Coast Ranges immediately to the west of the Marysville Buttes during the long interval of time represented by the Meganos formation.

SUTTER FORMATION

Succeeding the Butte gravels, at some places with a sharp contact and at others by almost insensible gradations, is a series of detrital volcanic tuffs and interbedded sediments to which Dickerson applied the name of the Sutter formation. In his description of this formation, Dickerson states[23] that

> . . . . resting with marked unconformity upon the Chico and the Tejon are 500–600 feet of strata which are composed chiefly of rhyolitic ash, rhyolitic tuff-breccia, thin flows of rhyolite and conglomerate containing rhyolitic and quartz pebbles. . . . . The materials in the Sutter formation were derived chiefly from the rhyolitic volcanic rocks (mapped by Lindgren as Nr), as the lava composing the thin flow noted above is identical with this rhyolite and some of the boulders in the conglomerate are likewise composed of this rock. The rhyolite areas mapped are in close association with the Sutter formation as a rule.

Dickerson considered the intrusion of the rhyolitic rocks (*Nr* of Lindgren's map) to have upturned and faulted the Cretaceous and Eocene beds. He supposed, moreover, that much of the Sutter formation was due to the "outpouring of rhyolitic flows and ash deposits" from these necks onto the faulted and folded sediments, and that, following these eruptions and prior to the intrusion of the central core of andesite, there was "a period of erosion during which a large portion of the Sutter formation was removed."

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[23] Dickerson, R. E., *op. cit.* (note 10), p. 404, 1916.

This original description of the Sutter beds calls for drastic revision. Essentially, the Sutter formation is the detrital equivalent of the Tertiary rhyolitic and andesitic deposits of the Sierra Nevada, admixed with sediments that are the equivalents in age of the "auriferous gravels of the intervolcanic period" of the Sierra. Although the Sierra was unquestionably the chief source of the Sutter beds, it is likely that part of the sediments was also derived from the Coast Ranges. The formation is composed principally of washed rhyolite tuffs, overlain by pyroxene and hornblende-pyroxene andesite tuffs, the pyroclastic material being admixed and interbedded with sands, clays, and gravels. It was deposited before the intrusion of both the andesites and rhyolites of the Marysville Buttes, and was involved in the folding and faulting consequent upon those intrusions. Its volcanic materials appear to be entirely pyroclastic and free from lava flows, and there is nothing in the formation to suggest a derivation from local vents, as Dickerson has supposed.

Distribution.—The full thickness of the Sutter formation is nowhere exposed, its upper members being overlain unconformably by the andesite tuffs and breccias that form the peripheral ring of the Buttes. Along the pass between Sutter City and West Butte—hereafter termed the West Butte Pass—the formation has a thickness of more than 1000 feet. Near West Butte, the exposed thickness never exceeds 600 feet, and it is likely that the formation thins in that direction. Along the northern slopes of the Buttes, the beds are poorly exposed, as about Pugh Place, or are wholly concealed. Along the eastern flank of the Buttes, however, they are finely revealed in a series of gentle folds. Here, in particular, they suffered extensive erosion prior to the period of local vulcanicity. In some places they were cut by deep, wide channels now occupied by andesite tuff and breccia, the products of the Marysville volcano; at others, especially along the weak fault zones, they were completely removed before those ejecta were deposited. It is probable, indeed, that many hundreds of feet of the Sutter beds were denuded from all sides of the Buttes between the period of laccolithic doming and that of the final andesitic eruptions. During that interval, also, the Sutter beds were entirely stripped from the top of the laccolith.

Lithology.—Perhaps the most notable and persistent feature of the Sutter formation is the regularity and prominence of its banding (pl. 15*a*). Had the materials been derived from the adjacent necks of rhyolite, as Dickerson believed, it is probable that they would exhibit a lenticular stratification due to an irregular overlap of the ejecta of different vents. On the contrary, the variations in the thickness and coarseness of the deposits bear no direct relation to those intrusions, suggesting, rather a general derivation from some source lying toward the east.

The most complete and typical section of the Sutter beds is to be found along the West Butte Pass, adjacent to the road bridge that lies due south of South Butte. The beds to the north of the road are disposed vertically or dip southward at steep angles, whereas in the higher parts of the section their dip gradually diminishes to about 40° southward, until they are concealed by the andesite breccias that dip in the same direction at angles of 10° to 12° (fig. 5). The basal members of the Sutter formation here consist of thin and irregular alternations of gray sands and silts and white rhyolite tuffs. The latter may be quite free from sedimentary admixture and are characterized by the presence of conspicuous fragments of opaque, white pumice and shredded glass in a gray matrix of fine rhyolitic dust and shards. With the exception of rare, broken crystals of acid plagioclase and sanidine and occasional spangles of pale brown biotite, these basal rhyolite tuffs are entirely glassy (pl. 17d). They bear a striking resemblance to and are probably the precise equivalents of the rhyolite tuffs that underlie the andesitic ''mud flows'' of the Sierra Nevada. Thin bands of rhyolite tuff occur at many other horizons in the lower part of the Sutter formation, but they become increasingly impure by admixture with sediment and andesitic material as they are followed upwards. The basal tuffs are succeeded by a rapid alternation of gray and buff sands, frequently rich in green and brown biotite and with various admixtures of rhyolitic and andesitic fragments, interbedded with siliceous gravels, the individual beds rarely exceeding three feet in thickness. It may often be observed that the pyroclastic content of the beds increases from below upwards, so that tuffaceous sediments give place to sedimentary tuffs.[24] It is noticeable, also, that as the content of andesite tuff increases, the sediments usually change from a gray to a buff or brown tint, though there are many exceptions to this rule. Moreover, in the coarser deposits, it is frequently possible to detect individual pieces of black, brown, and red andesite with the unaided eye. These lithic tuffs are intimately associated with crystal tuffs, entirely made up of incoherent chips of andesine and oligoclase, green augite, green and brown hornblende, and hypersthene, such as would result from the trituration of crystalline, basic andesite. The absence of non-volcanic constituents in some of these thin bands of crystal tuff suggests the possibility that the tuffs may have been dropped into place during periods of violent eruption of the Sierran volcanoes, and thus have escaped reassortment and washing. By far the greater proportion of the andesite tuffs, however, is of detrital origin.

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[24] The definitions of pyroclastic deposits adopted throughout this paper are those suggested by the writer in: Notes on the characters and classification of pyroclastic rocks. Proc. Liverpool Geol. Soc., vol. 14, p. 230, 1926.

The upper two-thirds of the Sutter formation in the area south of South Butte consist of interbedded brown, buff, and greenish-gray, micaceous sands, silts, and clays, with coarse gravels and pebbly layers, often current-bedded, and andesite tuffs that have suffered more or less addition of sediment. The pebbles in the coarser beds are well rounded and almost invariably siliceous, milky quartz, blood-red and red-brown cherts, black quartzites and gray schists predominating, with occasional ''greenstones,'' quartz-porphyries, and fragments of andesite. In these respects they simulate the fine members of the Butte gravels.

The variety of the andesites represented in the Sutter beds is such that the limits of space allow only a brief description of the dominant types. The following notes may, therefore, be taken to refer to the typical tuffs.

a. Evenly graded, coarse lithic tuffs consisting of subangular grains of dark gray, black, and reddish brown andesite, averaging 0.5 mm. in diameter, with a small proportion of crystal fragments, occur abundantly in the upper six hundred feet of the succession. The andesites include:

(1) *Augite andesite,* consisting of microliths and phenocrysts of andesine-labradorite with porphyritic and intersertal, pale green and colorless augite, attended by granular magnetite.

(2) *Hornblende andesite,* made up of microliths and squarish phenocysts of andesine in a feldspathic base clouded with magnetite and studded with large crystals of greenish brown hornblende. The hornblende shows Z $\wedge$ C, 15°, and the following pleochroism: *X*, pale yellow brown; *Y*, gray brown; *Z*, light brownish olive, and the crystals are usually outlined by granules of magnetite.

(3) *Feldspathic andesite* similar to the preceding, but with chlorite as the only ferromagnesian constituent.

(4) *Hypersthene andesite* showing glomeroporphyritic clusters of hypersthene in a matrix of plagioclase microliths of medium basicity.

(5) *Tachylitic andesites* or chips of vesicular glass, varying from almost colorless, through chocolate brown to black, and carrying microliths of andesine-labradorite together with much diffused magnetite dust, often limonitized.

Associated with these lithic inclusions are isolated crystals, chiefly of hypersthene, hornblende, and plagioclase (pl. 17*c*). The hypersthene occurs in rounded grains and has the following pleochroism: *X*, pale drab yellow; *Y*, yellow-green; *Z*, pale blue-green. Among the hornblende chips, the dominant type is dark green and shows *X*, mytho-green; *Y*, deep grape green; *Z*, deep blue-green to Lincoln green. The feldspars have a maximum basicity of about $Ab_{30}An_{70}$, the predominant varieties ranging from $Ab_{35}An_{65}$ to $Ab_{45}An_{55}$. They are often remarkably rich in inclusions of a colorless glass, so that they exhibit the spongy appearance which is characteristic of the porphyritic crystals of most pyroclastic rocks.

b. Accompanying the lithic tuffs described above are detrital crystal tuffs showing considerable sedimentary admixture. Among the principal constituents are fragmentary pyroxenes, both augite and hypersthene. The augite is usually pale green and exhibits no appreciable pleochroism; $Z \wedge C$, 35°; birefringence, .020; 2V, about 60°. An almost straight-extinguishing, highly birefringent, brown hornblende is also present, and with it a striking variety of hornblende in which *X* is pale yellowish green and *Y* and *Z* are shades of bluish and Hooker's green. The presence of tourmaline, epidote, colorless garnet, microcline, orthoclase, and quartz in these crystal tuffs clearly implies a sedimentary admixture.

c. *?Augite dacite tuff*, composed of angular chips of strongly zoned plagioclase (basic albite to acid andesine), rarely of orthoclase, quartz, and pale green augite, in a matrix of vitric shards and glass dust. There are also minute fragments of a clear, spun glass and of a beautifully banded cryptofelsitic lava that may be rhyolitic.

The andesitic constituents of the Sutter formation differ in many important respects from the andesite tuffs and breccias erupted from the Marysville volcano itself. The latter andesites are of a more acid character and are characterized by an abundance of green hornblende and biotite. They never carry brown hornblende, augite, or hypersthene. The plagioclase of the Marysville andesites is generally more acid and strongly zoned. Moreover, green biotite is either rare or absent among the Sutter tuffs.

Many of the features of the Sutter beds enumerated above, from the sections south of South Butte, are characteristic also of the exposures at other localities. About West Butte, however, the pyroclastic content of the deposits is much less evident. Gray clays, silts, and current-bedded quartz gravels predominate and occur in bands from six inches to a foot in thickness, with occasional streaks of buff-colored andesite tuff and detrital rhyolite tuff. In certain of the andesite tuffs, dark green and deep chestnut brown basaltic hornblende is extremely abundant. It is likely that on this western side of the Buttes the Sutter beds contain an admixture of detritus from the Coast Ranges.

Derivation.—It has been remarked already that the Sutter beds had been deposited before and were deformed by the intrusion of both the andesites and rhyolites of the Marysville Buttes. The fact that the beds thicken toward the east suggests that their principal source lay in that direction; the general diminution in the proportion of contained tuff toward the west also hints at an eastward source for the volcanic constituents. It has been noticed, moreover, that whereas rhyolite tuffs predominate at or near the base of the formation and become increasingly impure from lower to higher horizons, andesite tuffs predominate in its upper part. This general succession from rhyolite tuffs below to andesite tuffs above calls to mind at once a similar succession among the Tertiary volcanic rocks of the Sierra Nevada. When, further, the detailed petrographic characters of the latter rocks are compared with those of the Sutter tuffs, the similarities are seen to be so close that the probability of a common origin amounts almost to certainty.

When pure, the rhyolite tuffs of the Sutter formation are indistinguishable from the basal tuffs of the Sierra. Moreover, among the Sierran andesites, those which most closely resemble the andesitic fragments of the Sutter tuffs lie immediately to the east of the Marysville Buttes, that is, within the drainage-area of the Yuba River. Thus Lindgren states[25] in his description of the andesite tuff and breccia exposed about Nevada City and Grass Valley, forty miles east of the Marysville Buttes:

> This andesite is of a gray to brown or reddish color, hardly ever greenish, and is usually distinctly porphyritic, with small crystals of white feldspar and black augite or hornblende. As a rule, it has a rough, trachytic appearance. Mica is rarely found. Pyroxene (both augite and hypersthene) is almost invariably present. Black, basaltic hornblende frequently occurs with the pyroxene, and usually in larger crystals. The groundmass is glassy, or of a fine-grained, holocrystalline texture.

This description might be applied *verbatim* to the dominant types of andesite represented among the Sutter tuffs.

When a comparison is made with the Sierran volcanic rocks exposed at and below the village of Smartsville, only twenty or thirty miles east of the Buttes, the similarity is even closer. Among these rocks, the following types appear to be predominant:

a. Hornblende andesite. A pilotaxitic andesite composed of a felt of plagioclase laths ($Ab_{50}An_{50}$ to $Ab_{45}An_{55}$) relieved by large phenocrysts of basaltic hornblende and smaller phenocrysts and glomeroporphyritic clusters of a pale green augite. The hornblende shows remarkable pleochroisms, thus:

X	*Y*	*Z*
Pale yellow-green	Brown	Deep red-brown
Honey yellow	Pale chocolate	Chestnut

Its extinction, $Z \wedge C$, varies from 2° to 5°; its birefringence is about .070, and the mineral is usually outlined by granular magnetite. The augite is characterized by a very strong prismatic cleavage, $Z \wedge C$, 42°, and has an anomalous, wide optic axial angle. Its refractive indices are: α, 1.695; γ, 1.725; β, 1.702.

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[25] Lindgren, W., Nevada City Special Folio, no. 29, U. S. Geol. Surv., 1896.

b. Pyroxene andesite or andesitic basalt. Large, well-zoned phenocrysts of basic labradorite, and occasionally of bytownite, in a brown, limonite-stained, glassy base, carrying plentiful phenocrysts of green augite, hypersthene, and less commonly of basaltic hornblende.

c. Hornblende andesite. Strongly zoned phenocrysts of basic labradorite (Ab_{32} An_{68}), associated with green hornblende and augite, and occasionally with hypersthene, in a fine, partly glassy base. The pleochroism of the hornblende is: X, sage green; Y, yellow-green; Z, olive green.

d. Pyroxene andesitic basalt, with very abundant hypersthene phenocrysts and with basic labradorite as the principal feldspar.

All these rock-types occur among the Sutter tuffs. It is true that among the latter, the proportion of black, glassy andesites is generally high, and that among the few specimens examined from Smartsville similar andesites were not recognized, but the prevalence of green augite, hypersthene, and basaltic hornblende as the characteristic ferromagnesian minerals in both the Sutter and Smartsville tuffs suggests a common source. The peculiar optical properties of the augite and the distinctive pleochroism of the hornblende in all the rocks lend further support to their correlation.

At Sicard Flat, about two miles below Smartsville, the andesitic sands and conglomerates, together with the interbedded siliceous gravels, bear a still more striking resemblance to the Sutter formation, except that their materials are usually coarser.

No olivine-bearing basalts, such as those described by Turner,[26] in association with the Tertiary andesites of the Bidwell Bar and Downieville areas, have been distinguished among the Sutter beds. It may be suggested, therefore, that the volcanoes of the Downieville district did not contribute toward the formation of the latter. On the other hand, the andesites described by Lindgren in the Truckee, Colfax, and Nevada City Folios (18), are almost all of types that can be matched by the andesites of the Sutter tuffs.

The arguments cited above give reason to suppose that both the rhyolite tuffs and the andesite tuffs of the Sutter formation were derived from vents located in the Sierra Nevada directly to the east of the Marysville Buttes during the great Tertiary volcanic episode. These vents lay high up along the crest line of the range. About Nevada City, halfway down the western slopes, many andesite blocks exceed a foot in diameter; on the lower slopes, still farther from the vents, the ejecta are of much smaller proportions and exhibit an increasing admixture of sediment. Thus at Smartsville, the andesites are present as a compact tuff with "alternating strata of conglomerate or compact gravel," whereas below Smartsville, along the foothills of the Sierra, the andesitic material is said to be less than fifty feet in thickness and consists of a "black volcanic gravel or conglomerate, capped by a thin layer of andesitic breccia.[27] At Marysville, the andesite tuffs are still finer, fragments exceeding a quarter of an inch in length being extremely rare, and contain an even greater admixture of sediment. Traced away from the vents, therefore, the volcanic ejecta not only diminish in total volume, but the fragments become increasingly small and water-worn. A similar lateral variation of the Sierran volcanic deposits has recently been described by Louderback.[28]

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[26] Turner, H. W., Downieville Folio, no. 37, U. S. Geol. Surv., 1897; Bidwell Bar Folio, no. 43, U. S. Geol. Surv., 1898.

Much of the pure tuff present in the Sutter beds appears to have been deposited almost immediately after eruption. It is possible, indeed, that many of the torrents of andesite and rhyolite tuff debouched from the Sierran valleys with such vehemence that they spread far and wide into the Sacramento Valley without suffering much assortment or addition of sediment. Moreover, some of the finer tuffs, particularly those entirely composed of crystals, and the delicate fragments of rhyolitic pumice that occur at the base of the Sutter beds, may well have been borne to their present position by wind during the actual eruptions.

Throughout the eruptive period, there were short but vigorous intervals of erosion, during which much of the tuff mantle on the slopes of the Sierra was repeatedly denuded and redeposited in the Sacramento Valley. It is to these intervals of erosion that most of the detrital deposits of the Sutter formation are to be referred. The clastic sediments are so intimately admixed with the pyroclastic constituents of the Sutter beds, that they suggest at once a common derivation. This view receives additional support from the fact that, except on the western flank of the Buttes, there is apparently an absence of sediments that hint at a derivation from the Coast Ranges.

Lindgren [29] has summarized the evidence for the occurrence of several erosion intervals throughout the Sierran volcanic episode. During these periods of quiescence the streams cut new channels and deposited gravels along their beds. These are "the auriferous gravels of the rhyolitic, intervolcanic and andesitic epochs.'' Except that they contain fewer quartz pebbles and carry fragments of rhyolite, the gravels of the rhyolitic epoch do not differ materially either in character or composition from the preceding ''Bench gravels,'' all being essentially siliceous. Between the rhyolitic and succeeding andesitic eruptions, there followed a period of intense erosion during which deep channels were carved, not only into the earlier volcanic deposits and the ''Bench'' and ''Deep gravels,'' but, in places also, into the underlying ''Bedrock series'' to a depth of one hundred feet. This vigorous erosion is supposed by Lindgren to have been initiated by a tilting of the Sierra at the close of the period of rhyolitic eruptions.

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[27] Lindgren, W., and Turner, H. W., Smartsville Folio, no. 18, U. S. Geol. Surv., 1895.

[28] Louderback, G. D., Period of scarp production in the Great Basin. Univ. Calif. Publ. Bull. Dept. Geol. Sci., vol. 15, p. 17, 1924.

[29] Lindgren, W., The Tertiary gravels of the Sierra Nevada. U. S. Geol. Surv., Prof. Paper 73, pp. 28–29, 1911.

The gravels left along the lower slopes of the Sierra by the streams of the pre-volcanic and rhyolitic periods were thus subjected to further erosion and redeposition. Finally, during intervals between the andesitic eruptions themselves, rapid denudation ensued. In this way, throughout a prolonged period, the volcanic deposits of the Sierra, together with the interbedded and underlying gravels, were carried valleywards. Along the margins of the Sacramento Valley, under the influence of changing currents and similar factors, the gravels and volcanic detritus were still more thoroughly admixed. It is believed that the intermingled detrital tuffs and siliceous sands and gravels, still exposed along the course of the Neocene Yuba River, at Smartsville, Sicard Flat, and elsewhere, are precisely similar in composition to those of the Sutter group. This Tertiary river—''the largest of the streams draining the western slope'' of the Sierra—whose channel may be traced down to the sides of the Sacramento Valley, twenty miles east of the Marysville Buttes, may confidently be regarded as the source of much of the Sutter formation. There may well have been other contributory rivers to the northeast. At that time, the loads of these rivers were being emptied onto the floor of a shallow sea or bay, probably not very different in its limits from those of the present Sacramento Valley.

Erosion and westward transportation of the Sierran gravels and volcanic rocks continued after the close of the actual eruptive period, but whether or not that event occurred prior to the explosion of the Marysville volcano, it seems impossible to decide. The absence of any observable unconformities between the individual members of the Sutter formation suggests that the Sutter beds were laid down before the commencement of the laccololithic doming that finally gave rise to the Marysville volcano. The topmost horizons of the Sutter group, however, are nowhere to be seen.

Age and correlation.—Recently, Louderback[30] has stated that: "The period of great Tertiary andesitic eruptions in the Sierra Nevada is 'Middle Neocene,' that is, Lower Pliocene, or Upper Miocene, perhaps bridging the gap between these two epochs." If, therefore, the correlation between the Sierran andesites and the andesitic portion of the Sutter formation be accepted, then the latter should also be assigned to this age. The proviso must be added, however, that the topmost Sutter beds, which are unexposed, may belong to a still later period, having been transported from the Sierra after the final andesitic eruptions.

The age of the rhyolite tuffs that underlie the andesitic deposits of the Sierra is more uncertain, but is supposed, on the evidence of the associated flora, to be Miocene, and probably Lower Miocene. The possibility of an Oligocene age cannot, however, be dismissed. Whatever their age, that of the pure rhyolite tuffs at the base of Sutter formation is almost surely the same.

A tentative suggestion is offered that the Sutter beds may be, at least partly, the equivalents of the San Pablo formation (above the Briones division) of the Coast Ranges. Of this formation, Louderback[31] writes: "The distribution and character of the andesitic conglomerates of the San Pablo correspond well with a derivation from the Sierra Nevada during the period of andesitic eruption." The mode of origin which he postulates for these San Pablo beds varies only in detail from that suggested above for the Sutter tuffs. Moreover, there is a close lithological resemblance between many of the San Pablo and Sutter tuffs. Thus, for example, a specimen[32] of the former, collected from Kirker Canyon, north of Mount Diablo, contains abundant fragments of black, glassy andesite, together with chips of a pale green augite, hypersthene, and brown basaltic hornblende, and fractured crystals of labradorite, all of which are characteristic also of the Sutter tuffs. To judge from the absence of any notable admixture of quartz and clastic sediment, and from the angularity of the fragments, it would seem that some of the andesite tuffs of the San Pablo group, like some of those in the Sutter formation, were deposited almost immediately after explosion and suffered but little reassortment. The evidence for their common derivation from the Sierra Nevada is, therefore, strong. The fauna of the San Pablo beds was considered by Clark [33] to be ''Upper Miocene in age, possibly Lower Pliocene.''

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[30] Louderback, G. D., *op. cit.* (note 28), p. 19, 1924.

[31] *Ibid.*, p. 17.

[32] Specimen (no. 61) kindly loaned from the collection of Dr. V. T. Allen.

On petrological grounds, there is reason to suppose that the Oroville tuffs, which Lindgren believed to have been erupted from the Marysville volcano, are really equivalent in age to part of the Sutter formation and had a similar mode of origin.

THE MARYSVILLE IGNEOUS EPISODE

The history of igneous activity at the Marysville Buttes is, briefly, that of an andesitic laccolith from which the sedimentary cover was almost entirely stripped during and after intrusion, and of a volcano due to subsequent steam explosions from a central crater blasted through the core of the laccolith. These explosions appear to have been connected with the intrusion of a series of rhyolitic necks into both the andesites and surrounding sediments, after the latter had been eroded almost to their present level. The following notes attempt to trace this peculiar development of a volcano within a laccolith.

LACCOLITHIC INTRUSION

The central peaks of the Marysville Buttes are chiefly composed of a massive hornblende-mica andesite (andesite porphyry) and of ''propylites'' together occupying an approximately circular area about four miles in diameter (fig. 2). The actual contacts of this andesitic mass with the enclosing sediments are nowhere exposed. It is clear, however, that the contacts are in many places vertical, or are inclined outwards at high angles, so that the intrusion presents the appearance of an almost cylindrical stock. It is clear, also, that the mass was intruded after the deposition of most, if not all of the Sutter formation, for the exposed parts of that formation have everywhere been deformed.

The intrusion was probably a slow, aggressive process,[34] for there is no apparent evidence to indicate that it was initiated by any orogenic movements. Prior to the intrusion of the laccolith, it seems that its present site was occupied by more or less flat-lying sediments laid down in the persistent Sacramento Valley. This sedimentary roof, by reason of its lower specific gravity, may well have been arched upward by the invading andesite owing to the continued accession of fresh magma coming from below under pressure. Whatever the *modus operandi,* the sediments continued to yield to the intrusion by folding until such time as the strain was more readily relieved by fracture. In this way, the sedimentary cover was broken by a series of faults, disposed in general, both radially and concentrically with respect to the laccolithic margins (map). The radial blocks or sectors thus produced were then tilted outwards at different angles. Reference to the map and sections will show that the sedimentary block immediately south of South Butte was tilted almost to verticality, whereas the remaining blocks were tilted outwards at angles of from 10° to 40°, the blocks on the northern flank of the laccolith having the smallest outward dip.

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[33] Clark, B. L., Fauna of the San Pablo group of Middle California. Univ. Calif. Publ. Geol., vol. 8, pp. 385–572, 1915.

[34] In the sense defined by H. S. Palmer, Structure of the South Moccasin Laccolith, Ferguson County, Montana. Am. Jour. Sci., ser. 5, vol. 10, pp. 119–133, 1925.

Form of the Laccolith

The margins of the laccolith are almost everywhere indicated by an abrupt change of slope, and the exposed edges of the andesite are usually steep. About West Butte, for example, the outer face of the andesite dips outward at angles of about 70° within a few feet of the exposed sediments; at North Butte, the andesite rises in precipitous crags to a height of some 1300 feet above the adjacent sediments; along the southern slopes of South Butte, the margin of the andesite is related to the topography in such a way as to leave no doubt that it is nearly vertical close to the surface. Unfortunately, there appear to be few satisfactory criteria by which to determine the concealed form of the laccolith at greater depth. Some of these criteria may now be considered.

It will be observed from the map that the flanking sediments about West Butte are broken by a fault that runs almost parallel to the edge of the intrusion, and that the sediments on the outer side of the fault are upthrown with respect to those on the inner side, and that the former are tilted outward at higher angles than are the latter. Such a disposition suggests that the outer block may have been pushed up by an underground extension of the laccolith. If this be the actual case, then clearly the margins of the laccolith must flatten outward rapidly from the observed borders (fig. 7). Moreover, there is in the vicinity an andesitic intrusion, forming "852 Hill," the outcrop of which is detached from that of the main body in such a way as to suggest a stock-like offshoot from the central mass (fig. 6). On the southwest side of this hill, the sediments are gently domed, so that the Marysville and Ione formation are revealed below the Butte gravels. It seems probable that this doming is due to a concealed intrusion. To a similar cause are due, perhaps, the irregular folding and unequal tilting of the fault blocks at other localities. Thus, for example, the Chico beds exposed in the vertical block south of South Butte, exhibit, locally, abrupt changes from their normal east-west strike; again, certain minor folds in the southeastward plunging anticline among the sediments near Sutter City may be due to irregularities in the form of the concealed sides of the laccolith. The low northern dips of the sediments on the north side of the Buttes may indicate that there also the buried sides of the laccolith have a low outward dip. Considered on a large scale, the quaquaversal dips of the sediments enclosing the andesitic core, and the general tendency for the dips to diminish away from the igneous contact, appear to be more in consonance with the idea of a lacco-

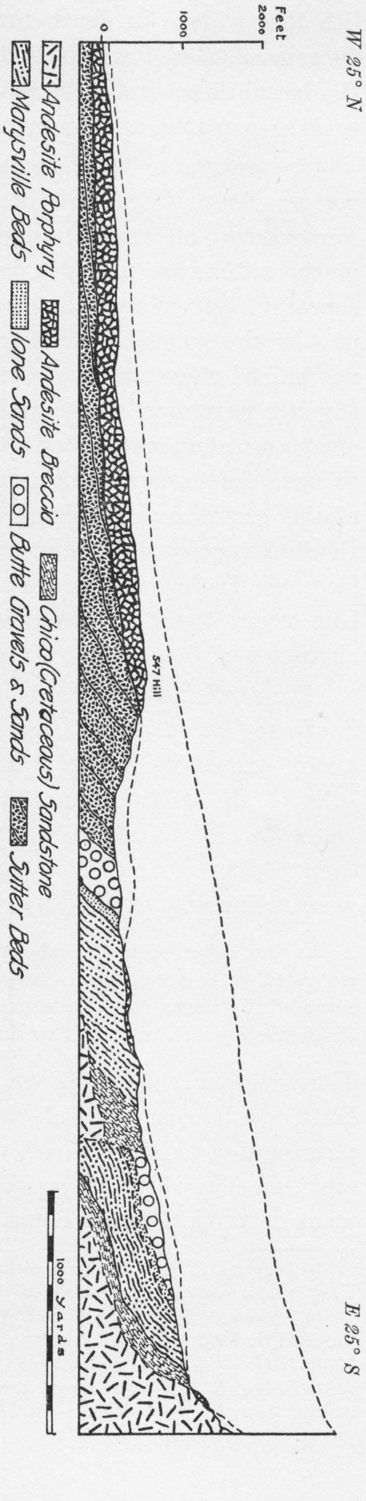

Fig. 7. Section across the west side of the Buttes; the broken lines indicate the approximate forms of the pre-eruption and post-eruption surfaces. Note the hypothetical, westward extension of the andesitic laccolith to account for the upthrow west of the fault.

lith that widens in depth than of a more or less cylindrical stock. In general, also, it seems that the flattening of the northern side of the laccolith occurs at shallower depths than along the eastern and western margins, and takes place most gradually to the south.

The general conclusion just stated, namely that the laccolithic margins flatten irregularly at depth, may be accepted with confidence. Nevertheless, although it may also be allowed that the minor folding of the sediments, to which reference has been made, resulted from concealed intrusions, there is no proof that those intrusions form a part of the andesitic laccolith. There is a possibility that many, if not all, of these minor dislocations are due to concealed bodies of rhyolite porphyry, for most of the exposed necks of porphyry that cluster so abundantly along the periphery of the andesite, are seen to have deformed the adjacent sediments. The clearest illustration of this occurs near the hamlet of West Butte, where an intrusion of rhyolite porphyry has upturned the Chico beds from beneath the Eocene. The disturbances attendant upon the intrusions of the rhyolitic necks therefore make it impossible to determine the precise character of the sides of the andesitic laccolith.

The available evidence tends to show that the Marysville laccolith is of the "steep dome" type, as defined by Jaggar.[35] Its sides are almost certainly concave upwards, recalling in this respect the laccoliths of the Judith Mountains, Montana.[36] This steep doming of laccoliths and the development of concave slopes have recently been discussed by Paige,[37] who has emphasized the importance of progressive increase of viscosity during intrusion:

> As the outer part congeals, the area in which pressure is transmitted is restricted, so that each successive application of pressure accentuates the upward curve of the strata over the source of supply of the laccolith, and the curve on the flanks of such a system would become more or less concave upward.

The observed margins of the andesite on the northern face of North Butte are almost vertical and are possibly due to faulting. It is possible also, though conclusive evidence is wanting, that much of the southern edge of the Marysville laccolith is a faulted one. The development of vertical faults along the margins of asymmetrical laccoliths has frequently been described, and Paige has shown that such faults are normally developed during the final stages of intrusion of viscous, steep-dome laccoliths. To summarize, it seems that the sides of the Marysville laccolith are concave upwards, and that their steeper upper parts may be largely faulted. We must now discuss the criteria relevant to the form of the top and of the bottom of the laccolith, and to the depth at which it was intruded.

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[35] Jaggar, T. A., The Laccoliths of the Black Hills. Twenty-first Ann. Rept. U. S. Geol. Surv., pt. 3, 1899–1900.

[36] Pirsson, L. V., and Weed, W. H., The geology and mineral resources of the Judith Mountains of Montana. Eighteenth Ann. Rept. U. S. Geol. Surv., pt. 3, pp. 437–616, 1897.

[37] Paige, S., The bearing of progressive increase of viscosity during intrusions on the forms of laccoliths. Jour. Geol., vol. 21, pp. 541–549, 1913.

It is obvious that if the sediments, as now exposed, were depressed to a horizontal position they would not cover the area at present occupied by the andesitic laccolith. The vertically bedded sediments along the West Butte Pass cannot continue in depth at verticality to any great distance; indeed, the evidence from deep borings at Marysville, ten miles distant, suggests a rapid flattening to horizontality. The remaining sedimentary blocks, even when depressed to horizontality, would not extend far beyond their present outcrops. It follows that there has been considerable erosion of material from the center of the Buttes, though it is impossible to assess with accuracy the amount of this erosion. There are, however, certain clues to which attention may be directed.

To the south of South Butte, the sediments are disposed almost

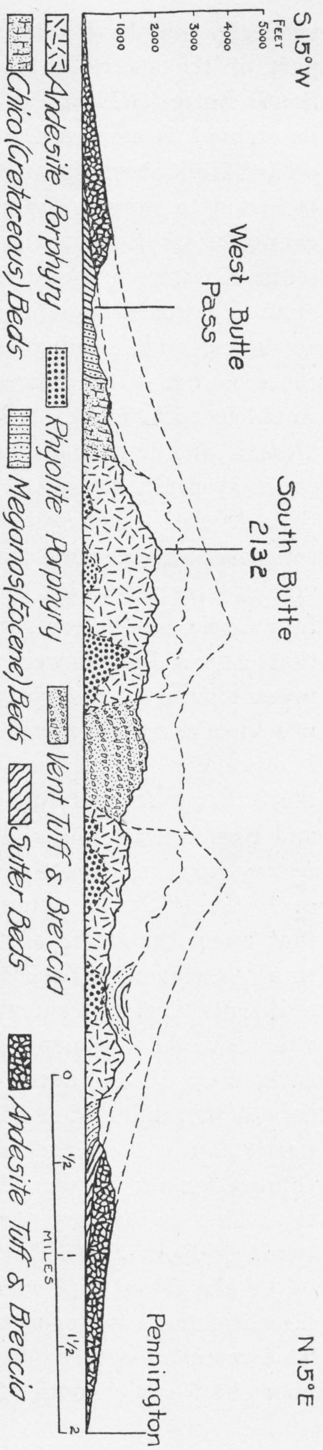

Fig. 8. Generalized section across the Marysville Buttes, illustrating the supposed forms of the pre-eruption and post-eruption surfaces in relation to the present topography.

vertically and have a thickness exceeding 4500 feet, the uppermost part of the succession being concealed beneath andesitic breccias. South Butte itself has an altitude of 2132 feet above sea level, and its summit is composed of andesite. How much andesite has been eroded from above the summit it is impossible to determine, but there is reason to suppose, as we shall see later, that the present summit cannot be much below the original top of the laccolith. If, then, the sediments were arched over the andesite at this point, the resultant mountain would be at least 6000 feet high, even allowing for slight stretching and thinning of the sediments on the dome. If, further, the alluvium of the Sacramento Valley were removed, the mountain would be still higher. An almost vertical-sided mountain of such an altitude and having a diameter at the base of only about five miles probably could not exist. Accepting this line of argument, it seems that the full thickness of sediments exposed about West Butte Pass can never have covered the laccolith. There is, however, a more convincing reason for this belief. The low outward tilt of the sedimentary blocks on the east, west, and north sides of the Buttes is such that if the sediments were projected over the andesitic core with their present or even a slightly higher dip, they would in many places provide a cover not more than a few hundred feet in thickness. This is especially true of the sediments about North Butte. Hereabouts, the Sutter tuffs and Butte gravels dip northeastward at 10° or 15° and pass beneath the andesite breccia at an elevation of about 500 feet (map), whereas the andesite of the laccolith attains a height of 1863 feet, on the summit of North Butte, only one-half mile distant along the strike of the sediments (fig. 9). To ensure even a thin cover over that portion of the laccolith about North Butte, the sediments must suffer a sudden arching. A consideration of the map will show that at many localities the laccolith can only have been covered by a thin veneer of sediments (in places only by the Sutter formation), unless it be admitted that the margins of the laccolith are partly faulted. In general, it seems that the sedimentary cover was thinnest on the north and east sides of the laccolith. Indeed, there is nothing to disprove the assertion that parts of the laccolith, particularly about North Butte, projected through the sedimentary roof.

Of the actual roof which formerly covered most, if not all of the laccolith, there is apparently only one small remnant now in place. This remnant is to be found on the northern side of the laccolith, about half a mile south of Pugh Place. Here occur many exposures of dark mudstone and greenish-gray siltstone invaded and baked by propylitized andesites and rhyolite porphyries. The precise structure of the sediments cannot be determined, but it seems, from the absence of xenoliths at all other localities within the andesite, and from the size of these exposures, that we are dealing here with part of the base of the sedimentary cover. On lithological grounds, the sediments may be identified with assurance as belonging to the uppermost portion of the Marysville (Meganos) formation. If this identification be valid, then the laccolith at this point cannot have been covered by more than 1500 feet of sediments, and may well have been under a still shallower roof. The apparent absence of Chico (Cretaceous) beds in the original sedimentary roof on the north and east sides of the laccolith gives additional reason for the doubt, already expressed, that the full Cretaceous-Tertiary succession about West Butte Pass formerly covered the laccolith at South Butte. If that succession once covered the andesite at South Butte, then there has been a removal of at least 4500 feet of material; but over parts of the north side of the Buttes only 1500 feet were removed. Such an unequal rate of erosion of the sedimentary cover seems unlikely; it is more feasible to suppose that the Chico (Cretaceous) beds, at least, never covered South Butte.

The top of the laccolith was not only beneath a cover of uneven thickness, but was itself probably very irregular. Thus, for example, the altitude of the top of the laccolith beneath the sedimentary outlier, is only about 400 feet, whereas one-quarter mile to the northeast, the andesite reaches an altitude of almost 850 feet, and may have been much higher, and on North Butte, less than one and a half miles distant, it rises to 1863 feet. Again, a steep-sided offshoot from the main laccolith rises some 500 feet above the intervening sediments to the north of West Butte. Moreover, the laccolith itself appears to be composed of a number of more or less discrete intrusions, which find topographic expression as a series of isolated hills and crags, separated by deep ravines. The structures of the andesite in these units, although often vague, are sufficient to warrant the assertion that the magma was intruded in masses that were partly individualized. North Butte itself is almost certainly a discrete intrusion. The petrographic uniformity of the andesites, however, suggests that no long period of time intervened between the separate intrusions. It may be that a series of irregular or conical protrusions issued from the top of the main magma reservoir, and that some of these protru-

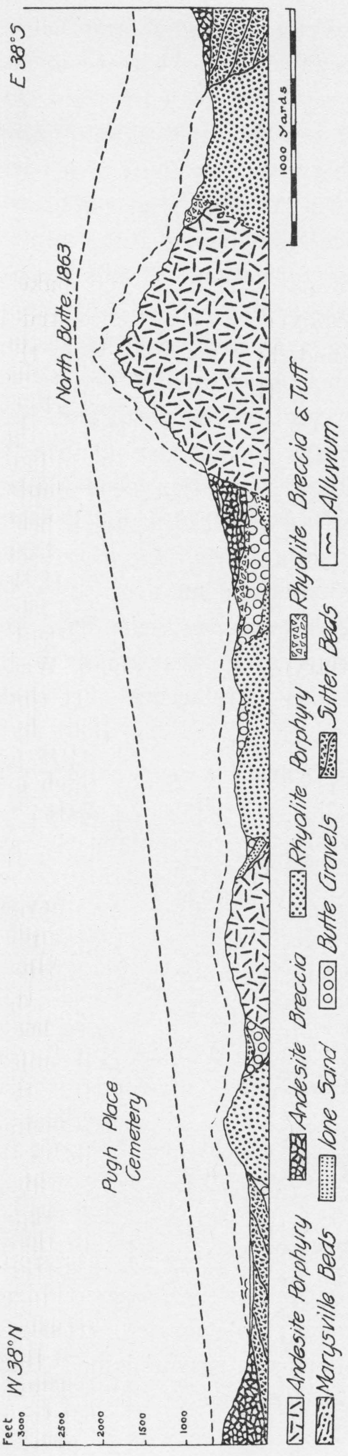

Fig. 9. Section through North Butte; the broken lines indicate the approximate forms of the pre-eruption and post-eruption surfaces.

sions actually reached the surface. The maximum thickness of the sedimentary cover may not have exceeded 2000 feet.

The irregular top that is here postulated for the laccolith resembles in many respects that of the quartz diorite ''batholith'' of the Marysville district of Montana, so admirably described by Barrell.[38] Discussing the form of the Marysville ''batholith,'' Barrell states that its upper surface ''instead of being more or less regular, is extremely irregular, steep or vertical surfaces alternating with flat surfaces, giving the whole a rudely pyramidal form with a somewhat step-like surface from which project dikes, sheets and chimneys.'' The ''satellitic chimneys'' rising from the top of the Marysville ''batholith'' are in places more than a quarter-mile high and have almost vertical walls. They recall the steep-sided offshoots on the upper surface of the Marysville laccolith, and particularly the mass of andesite that forms North Butte. In the Montana ''batholith,'' however, stoping or subsidence of roof-blocks has been a dominant process, whereas at Marysville, California, no such action appears to have taken place.

Finally, it is obvious that if we accept the identification of the remnant of the sedimentary roof as part of the Marysville formation, then the base of the laccolith must be transgressive. Indeed, on the south side of the Buttes, the base of the laccolith is from 1600 to 1700 feet lower stratigraphically than it is on the north side, for on the south side over 1460 feet of the Chico beds and some 200 feet of the Marysville beds are upturned on the flank of the laccolith, and these beds all lie stratigraphically below the remnant of the sedimentary roof on the north. The plane of intrusion thus rises sharply northward.

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[38] Barrell, J., Geology of the Marysville mining district, Montana. U. S. Geol. Surv., Prof. Paper 57, 1907.

In later paragraphs a description will be given of a crater, about a mile in diameter, which was blasted through the core of the laccolith. The ejecta that issued from this crater were almost wholly of igneous origin. It is certain, therefore, that the vent was not drilled through any great thickness of sediments beneath the laccolith and that most of the sedimentary cover had been stripped from above the crater prior to the explosions. If we assume that the crater lies immediately above a large, more or less vertical feeder at the base of the laccolith, we provide a ready explanation for this paucity of sedimentary ejecta. There may well have been other minor feeders to the laccolith, especially below the discrete conical intrusions, such as North Butte.

Mode of Intrusion

It seems reasonable to suppose, on petrological grounds, that the andesite of the Marysville laccolith crystallized slowly and under singularly uniform conditions. The coarsely porphyritic texture and remarkably uniform crystallinity of the andesite, despite its great extent, point to such a slow solidification. Moreover, there is a notable absence of a well-developed chilled phase in the intrusion. Not only are the observed margins coarse grained, but, since only rare specimens of quickly chilled, fine-grained, andesites occur among the peripheral breccias, which represent part of the top of the laccolith shattered by later explosions, it follows that the upper margins of the mass were also, for the greater part, coarsely crystalline. At the time of its intrusion, the magma must have been of extreme viscosity; otherwise it is difficult to account for the striking absence of narrow veins and dikes along the margins of the laccolith, especially since the adjacent sediments were abundantly fractured by the intrusions and that the resultant fault planes would have offered a ready passage for the magma. The absence of vesicularity throughout the andesite may be due to a low content of volatiles in the parent magma; in turn, such a dearth of volatiles might explain the viscosity of the magma, the paucity of flow-structures and perhaps also the abnormally small degree of contact metamorphism suffered by the contiguous sediments. Moreover, the intrusion of the laccolith was unattended by explosions or flows of lava, despite the thinness of most of the sedimentary cover. Indeed, the andesite may actually have reached the surface locally, as already suggested, and have been too viscous to spread laterally to any great extent. It may be that the magma had already undergone considerable crystallization before emplacement, so that if it ever reached the surface it was then largely solid.

Robinson [39] has described a somewhat analogous phenomenon at Elden Mountain, Arizona, which "combines, it is believed, what may be properly called laccolithic intrusion with volcanic extrusion." There, the invading magma turned aside the surrounding blocks of sediment, as on separate hinges, and rose in contact with the air. It cannot be proved, but it is probable that parts of the Marysville laccolith, and in particular that part which forms North Butte, were injected in a similar manner. Such surface protrusions would partake of the features of other "massive-solid volcanic eruptions," such as those described by Russell [40] from the Mono Craters, and by the writer [41] from about Lassen Peak. But whereas the protrusions at Mono and Lassen are of obsidian and glassy dacite, respectively, the andesite of the Marysville laccolith is almost wholly crystalline. The Marysville andesite certainly cooled more slowly. Parts of the andesite may indeed have been pushed up bodily in an almost solid condition, as was the hornblende-mica andesite forming the precipitous Bogoslof Island, Alaska, or the spine of Mont Pelée, or the dacite plug in the crater of Lassen Peak. Such an upthrusting of more or less solid material would of course result in the fracturing and faulting of parts of the laccolith.

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[39] Robinson, H. H., The San Francisco volcanic field, Arizona. U. S. Geol. Surv., Prof. Paper 76, pp. 74–85, 1913.

[40] Russell, I. C., Criteria relating to massive-solid volcanic eruptions. Am. Jour. Sci., ser. 4, vol. 17, pp. 253–268, 1904.

[41] Williams, H., A recent volcanic eruption near Lassen Peak, California. Univ. Calif. Publ. Dept. Geol. Sci., vol. 17, pp. 241–263, 1928.

STRUCTURE AND PETROGRAPHY OF THE ANDESITE PORPHYRY OF THE LACCOLITH

There are few features of the Marysville laccolith that strike the observer more readily than the remarkable petrographical homogeneity of its rocks. Despite the fact that the andesite porphyry occupies an area exceeding ten square miles, it shows surprisingly little variation other than that due to the local action of hydrothermal solutions, producing "propylites." Lindgren describes the dominant rock as a "normal, hornblende-mica andesite of very rough, trachytic appearance" and states that "the rock type does not correspond to any found on the western flank of the Sierra Nevada, but shows the closest analogy with the latest effusive masses from the Comstock and Bodie."

What is the internal structure of the laccolith? Unfortunately, the answer is made difficult by the absence of continuous exposures within the mass and by the fact that it appears to be composed of a succession of more or less distinct intrusions. There are certain features, however, that are very clear. In general, it may be said that the banding of the andesite flattens toward the higher parts of the mass, as if the present peaks of the Buttes are not far below the original top of the laccolith, for we should expect the banding in the topmost parts of the intrusion to conform in a broad way to the shape of the sedimentary roof. Except along the northwest border of the laccolith, where the banding dips outward at about 30° (pl. 15*b*), the flow-planes are almost invariably vertical or dip at high angles, a feature that indicates the laccolith to be of the "steep-dome" type, as suggested already on other grounds. Throughout North Butte, for example, the banding rarely departs greatly from the vertical. On the top of South Butte and the adjacent crags, however, the banding is either horizontal or rolls at low angles, whereas two hundred or three hundred feet below the summits it is usually vertical. This change in the attitude of the flow-planes may not be unconnected with proximity to the original roof of the laccolith.

It is worthy of especial note that there is no "stratification" or layering within the intrusion that might hint at even a partial differentiation of the andesite either during or following its injection. On the contrary, the minor petrographical differences that occur within the mass appear to be of quite irregular distribution.

There is, moreover, little prismatic structure in the andesites, save at one locality on the eastern margin of the laccolith, where the columns are vertical (pl. 15*c*). An original jointing is commonly developed perpendicular to the flow-planes, but the regular system of joints found by other workers to be characteristic of many large plutonic intrusions is here conspicuously absent. Even on adjacent hills, the joint systems appear to be differently oriented, as if the hills represent more or less discrete intrusions rising from the main body of the laccolith as ''satellitic chimneys.'' It must be assumed that the absence of prismatic jointing throughout most of the laccolith implies a relatively slow rate of cooling or that the andesite was already partly or even largely crystalline prior to its final emplacement. Gilbert has drawn attention to a similar dearth of prismatic structures among the laccoliths of the Henry Mountains, Utah.

Equally significant is the scarcity of vesicles among the Marysville andesites. Neither in the observed margins of the laccolith, nor in the andesite tuffs and breccias that represent part of its shattered top, is vesicularity more than a trivial feature. Usually, the margins of the intrusion are massive and as coarse-grained as the interior.

Finally, the andesite porphyry may be strongly auto-brecciated. This brecciation may be localized along narrow bands separated by layers of massive andesite, or it may effect the intrusion over wide areas, as for, example, one mile northeast of South Butte (plate 10*c*). The fragments of these breccias are usually angular and seldom exceed two inches in length, being dispersed irregularly in a base of massive andesite, as if due to the upwelling of fresh magma between blocks of previously consolidated material. It is possible that many of the deep, brush-covered valleys that traverse the laccolith are etched along such zones of brecciation, but adequate proof for this assertion is wanting.

Petrography of the andesite porphyries.—We may now discuss the petrography of the andesite porphyries and of their alteration-products, the ''propylites.'' The typical, coarse, pale green rock of the laccolith, such as forms North Butte, South Butte, and West Butte is notably porphyritic. Occasionally, indeed, the feldspar phenocrysts reach a length of an inch, and both biotite and hornblende are usually discernible to the unaided eye. In general, the andesites are crystalline throughout, but they may be partly glassy. In some specimens, biotite may be absent (pl. 19*e*), but hornblende is always present. The coarser-grained rocks are deeply weathered and give rise to a thick, rich, chocolate brown soil; the "propylites," too, are so amenable to decomposition that they are rarely exposed and usually form low, rounded hills.

Microscopical petrography.—Considering first the porphyritic constituents, the plagioclase occurs in crystals that average three times as long as broad and is always strongly zoned. Indeed, the zoned character of the feldspars is perhaps the most striking feature that the rocks possess. The dominant variety is a basic oligoclase ($Ab_{75}An_{25}$), the most basic type being andesine ($Ab_{60}An_{40}$). Many of the crystals are broken; others are rounded or resorbed and embayed in a curious fashion (pl. 19*a*) and carry zonally arranged inclusions of an irresolvable gray dust. Frequently, the crystals have a narrow, glassy rim separated from a glassy core by a broad, clouded zone that is full of dust and partly kaolinized. Other phenocrysts are abnormally charged with idiomorphic and sub-idiomorphic inclusions of hornblende and biotite. In most of the andesites there is a noteworthy absence of decomposition among the porphyritic feldspars, so that epidote, calcite, and kaolin are extremely rare.

The hornblende is always green, and may be well zoned in various shades of that color, the tints being deepest in the cores of the crystals. Among the andesites of the Sierra Nevada, on the contrary, both the biotite and hornblende are usually brown, and the latter mineral is normally of the basaltic variety. In size, the hornblende phenocrysts of the Marysville rocks range up to 2.5 mm. and average 0.2 mm. in length. Twinning on (100) is common. The general pleochroic scheme is as follows:

X	*Y*	*Z*
yellowish green	pale blue-green	deep blue-green

$Z \wedge C$ varies between 15° and 18° and the birefringence is about .020. 2V, 85° to 88°. In some andesites, the hornblende is thoroughly decomposed and is then replaced by chlorite and calcite, the iron being rejected toward the crystal edges as granular magnetite. Inclusions of both biotite and plagioclase may occur within the hornblende and may be definitely oriented with respect to the cleavage of the host. Occasionally, diopside is preserved in the cores of the hornblende (pl. 19*d*), but pyroxene is normally confined to the basic segregations, to be described hereafter.

The biotite is more irregular in its distribution than is the hornblende and is wholly lacking in many andesites. It is generally of a greenish brown color and shows a pleochroism thus:

X	*Y* and *Z*
pale yellow-green	dark brownish green

Though dominantly pale green, some crystals may have a dark olive-green or even brownish nucleus, but the reddish brown biotite characteristic of many of the Sierran andesites and of the reheated andesite tuffs and breccias at Marysville is never seen among the fresh andesites of the laccolith. The biotite and hornblende are often associated as glomeroporphyritic clusters or may be intimately intergrown, but both minerals are capriciously oriented in the flow-planes.

Minute granules and octahedra of fresh magnetite are dispersed throughout, as inclusions within the phenocrysts and in the base. Apatite is a constant and important accessory, just as it is among the later rhyolite porphyries.

The groundmass of the andesite porphyries is usually pilotaxitic, consisting of microliths of acid andesine and oligoclase in a cloudy, feldspathic matrix. The possibility has not been precluded that some of the untwinned microliths of the groundmass may be orthoclase. The glass produced by artificially heating the matrix has a refractive index of 1.505, which corresponds to a silica percentage of seventy. In some andesites, the base is almost devoid of microliths and is a cryptogranular mosaic of feldspar, probably with some quartz. In other rocks, the feldspathic base has a cryptographic texture, or is partly glassy, and every gradation exists between the several types.

Propylites.—The term "propylite" is used here in the sense in which it was employed by Judd,[42] namely, as a useful, descriptive field name for altered andesites. It is preferred to the term meta-andesite since it implies the hydrothermal character of the alterations.

The Marysville propylites are distributed quite irregularly within the laccolith, as is natural in view of their mode of origin, but are most extensively developed in its northern part, adjacent to the remnant of the sedimentary roof, and along the southern margin of the intrusion. They resemble closely the propylites first described by Richtofen[43] and those later described by Zirkel[44] and Becker[45] from Nevada and by Judd[46] from Scotland, so that only a brief mention of their characters seems necessary here. Their chief features are their dull green color, the absence of fresh hornblende and mica and their opaque, decomposed feldspars. They are usually much finer grained than the normal andesites, but frequently the rocks may be observed to grade into each other, just as Becker describes the gradations from andesites to propylites in the Comstock Lode, Nevada. Briefly, the propylitization of the Marysville andesites involves:

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[42] Judd, J. W., The propylites of the western isles of Scotland, etc. Quart. Jour. Geol. Soc., vol. 66, pp. 341–385, 1890.

[43] Richtofen, F., Mem. Calif. Acad. Sci., vol. 1, 1868.

[44] Zirkel, F., Microscopic Petrography, vol. 6, U. S. Geol. Exploration of the Fortieth Parallel, pp. 110–121, 1876.

[45] Becker, G. F., Geology of the Comstock Lode and the Washoe district, U. S. Geol. Surv., Mono. 3, 1882.

[46] Judd, J. W., *op. cit.*, 1890.

COMPARATIVE ANALYSES

	1	2	3	4	5	6	7	8
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
SiO_2	60.84	55.42	59.97	60.20	66.88	58.24	58.07	58.65
Al_2O_3	17.86	19.47		17.21		16.69	17.62	17.90
Fe_2O_3	2.59	3.43		3.12		3.37	4.97	
FeO	1.72	2.50		2.69		1.22	3.09	4.11
TiO_2	0.18	0.32		0.57		Trace		
CaO	5.24	6.96	6.09	6.04	3.54	4.62	5.23	5.87
BaO				0.11				
MgO	3.05	5.59		3.18		3.15	1.46	2.03
MnO	0.16	0.13		0.12		0.25	Trace	
K_2O	2.48	1.88	1.35	1.44	1.84	2.46	2.15	3.19
Na_2O	3.80	2.95	3.98	3.35	4.62	2.70	3.31	2.07
H_2O+	0.50	0.40		1.12		0.48		
H_2O-	1.20	0.75		1.18		4.24	4.15	6.53
CO_2	Nil					2.16		
P_2O_5	0.26	0.33		0.17		0.12		
S	Trace							
Cl	Trace							
Totals	99.88	100.13		100.50		99.70	100.05	100.35

1. Hornblende-mica andesite porphyry; summit of South Butte, Marysville. Analyzed by W. H. Herdsman.
2. Hornblende-mica andesite porphyry (74); one mile west of South Butte, Marysville. Analyzed by K. Willmann.
3. Hornblende-mica andesite
4. Hornblende andesite
5. Hornblende-mica andesite

(3–5) Quoted by H. W. Turner, "The Igneous Rocks of the Sierra Nevada." U. S. Geol. Surv., Fourteenth Ann. Rept., pt. 2, p. 490, 1892.

6. Propylitized andesite porphyry; one mile south of Pugh Place, Marysville Buttes. Analyzed by K. Willmann.
7. Propylite; Mull, Scotland. Analyzed by G. H. Perry, quoted by J. W. Judd, Quart. Jour. Geol. Soc., vol. 66, p. 349, 1890.
8. Propylite; Washoe, Nevada. Analyzed by W. G. Mixter, quoted by G. F. Becker, U. S. Geol. Surv., Monograph 3, p. 152, 1882.

a. The replacement of the hornblende by chlorite, calcite, and mica and a separation of titanite and granular magnetite. Often, the magnetite is segregated along the margins of the deceased hornblende crystals, outlining them with a distinct, black border, or it may follow the cleavage cracks of the parent (pl. 19*c*). The secondary chlorite and pale green mica may be so intergrown that the flakes lie flat along the pinacoidal cleavages of the hornblende.

b. A bleaching and shredding of the biotite. This process may be so advanced that the original green biotite is replaced by colorless mica and granules of magnetite.

c. A decomposition of the feldspars with the formation of calcite and kaolin.

d. The formation of patches and veins of quartz mosaic.

It is noteworthy that pyrite, abundant among the propylites of Nevada, is either very rare or absent among the Marysville rocks. For the formation of the latter, there seems to be no need to invoke any action other than that of heated waters and carbon dioxide acting upon the andesites.

Chemical composition.—On p. 153 are given two analyses (1 and 2) of the Marysville andesite porphyries. Specimen No. 1, from the summit of South Butte, is of a typical, coarsely porphyritic, pale gray, hornblende-mica andesite, and may be considered as the dominant rock of the laccolith. Specimen No. 2 is from the west slope of "1381 Hill," one mile west of South Butte, and is representative of the darker, fine-grained andesite porphyries, with a partly glassy base and poor in biotite. The silica percentage of the latter rock is unusually low by comparison with most hornblende-mica andesites; its alumina, ferrous iron, and magnesia contents are correspondingly high. Partial analyses of three andesites from Plumas County, California, are added for comparison (3, 4, 5).

Considering their mode of formation, propylites naturally differ widely in composition. The typical Marysville propylite (analysis no. 6) is noteworthy for its high content of combined water and carbon dioxide, but is otherwise probably not very different from the average andesite porphyry. Analyses of two other propylites are appended for comparison.

BASIC INCLUSIONS IN THE ANDESITE PORPHYRY

Near the northern margin of the laccolith, immediately to the north of the remnant of the sedimentary roof, the andesite contains a few widely scattered basic inclusions. This is the only locality at which such inclusions have been found *in situ* within the andesite, though similar basic rocks are occasionally to be found among the andesite tuffs and breccias on the lower, peripheral slopes of the Buttes and are very plentiful among the bedded pyroclastic rocks that rest upon the laccolith, one-quarter mile west of the remnant of the sedimentary roof. The precise source of the basic rocks among the latter deposits is unknown.

Where they are observed *in situ* within the andesite, the distribution of the inclusions is quite irregular. They are extremely rare; it is, indeed, exceptional to find more than one or two inclusions within one hundred square yards of outcrop of the andesite, though occasionally three or four may be observed within the space of ten square yards. The inclusions range from about one-quarter inch to seven inches in length; in shape, they are variable, though most are distinctly angular, and their contacts with the andesite are always sharp. They appear to show no regular orientation with respect to the flow-planes of their andesitic matrix.

Mineralogically, the inclusions consist essentially of green hornblende, with or without diopside, mica, and feldspar. Texturally, they exhibit every gradation from dense aphanitic types to coarse, gabbroid facies, and not only may the most divergent textures be seen in adjacent inclusions, but they may also occur within individual specimens. Occasionally, a distinct gneissose structure results from the alternation of thin layers rich in mica and hornblende with layers rich in feldspar, and such a structure may give place rapidly to granular intergrowths of the same minerals.

Taken together, the inclusions present a gradational series, commencing with specimens rich in diopside and ending with others rich in mica. In the most basic types, kernels of diopside are surrounded by rims of hornblende, and mica is absent. The content of hornblende increases in proportion as diopside diminishes in amount, and mica is only developed where diopside is either very rare or entirely absent. The feldspar throughout is of medium basicity and is invariably more basic than the feldspar of the normal andesites. In view of the gradational series noted above and considering also that the mineralogical content of the most acid specimens closely resembles that of the andesites, it seems probable that we are dealing here, not with xenoliths, but with cognate inclusions or autoliths. The sharp borders and angularity of the inclusions indicate that they were finally floated to their present positions in a more or less solid condition.

Microscopic characters of the inclusions.—Under this heading, it seems best to describe the inclusions in the order of decreasing basicity. Reference to plate 18*e* shows the characteristic texture of the diopside-rich inclusions. The diopside, which is colorless or very pale green, has an optic axial angle, 2V, of 65° to 70°; its extinction angle, $Z \wedge C$, is 38° and the birefringence is about 0.030.

It is altered both peripherally and along its cleavage-cracks into massive and fibrous pale green hornblende. The pleochroism of the hornblende is from pale yellow-green, *X*, through pale olive green, *Y*, to deep sage green or blue green, *Z*. Locally, the hornblende is developed in hypidiomorphic, granular aggregates free from diopside. The matrix between the ferromagnesian minerals is a coarse mosaic of medium labradorite, the average size of the grains being about a millimeter. Abundant specks and microliths of diopside and minute granules of magnetite are scattered throughout the feldspar and give it a dusty appearance. Titanite is exceptionally common, and almost always carries sub-idiomorphic magnetite and yellow-brown crystals of rutile. This abundance of titanite is in marked contrast to its paucity in the normal andesites. Apatite is also plentiful, as may be judged from the analysis (9), and occurs indiscriminately throughout.

Some of the inclusions consist of about 95 per cent hornblende, with rare grains of magnetite and apatite and a little interstitial labradorite. The texture of such inclusions is hypidiomorphic to granular, the prism faces of the hornblende usually being well developed and their terminations ragged. Some of the crystals are 3 mm. long, but the average length is about 0.5 mm. The pleochroism of the hornblende is, *X*, pale yellow-green, *Y*, pale olive green, *Z*, deep yellowish or bluish green. The extinction angle $Z \wedge C$, is 24°, and the refractive indices are α, 1.660, γ, 1.682. Exceptionally, the crystals are twinned on (100), but generally they are untwinned.

In some of the specimens, hornblende and feldspar are intergrown in a granular mosaic that passes into a hypidiomorphic granular texture where the minerals are of larger dimensions (pl. 18*d*). Locally, there are remarkably equigranular mosaics of untwinned labradorite, the rounded grains varying but little from 0.12 mm. in diameter, which recall textures often seen in contact metamorphic rocks. The hornblende may also be segregated in equigranular mosaics within the feldspar, the average grain size being about 0.25 mm. Fresh magnetite is dispersed irregularly throughout, often in large plates, and apatite is abundant in stumpy, rounded prisms. Occasionally, granular and dusty magnetite may be present as thin rims surrounding the hornblende crystals and separating them from the feldspathic base.

Finally, in the coarse-grained inclusions, biotite is developed either along the margins of the hornblende crystals, or as inclusions within them or again as irregular intergrowths (pl. 18*f*). The pleochroism of the biotite is *X*, dull yellow-gray, *Y* and *Z*, brownish black.

Green biotite, similar to that found in the normal andesites, has not been observed. In these inclusions, the feldspar forms a coarse mosaic and is strongly twinned both on the albite and pericline laws. It ranges in composition from medium labradorite to basic andesine ($Ab_{40}An_{60}$ to $Ab_{52}An_{48}$), labradorite predominating. Apparently, part of the feldspar crystallized along with the hornblende, for the minerals contain inclusions of each other. Both titanite and apatite are abundant, and the latter is occasionally developed as stout, rounded and embayed crystals up to 2 mm. in length.

Apart from the obvious textural differences between the mica-rich inclusions and the normal andesites (cf. pl. 19, *b*, *d*, and pl. 18*f*), there is a conspicuous absence of zoning among the feldspars of the inclusions whereas that feature is characteristic of the feldspars in the andesites. Indeed, none of the minerals of the inclusions is zoned, though in many andesites, the hornblende and biotite, in addition to the feldspar, show that structure to perfection. These differences may imply that the inclusions crystallized under more uniform conditions. That the accessory minerals, apatite and titanite, are relatively more abundant among the inclusions is to be expected.

Chemical composition. — Chemically, the transition from the diopside-rich to the mica-rich inclusions, and lastly to the normal andesites, involves a relative loss of lime and iron and an increase in alkalies and silica. It is possible that the concentration of volatiles during the crystallization of the parent magma partly explains the formation of the biotite in the later stages.

Below is given an analysis of the most basic type of inclusion, namely the diopside-rich inclusion figured (pl. 18*e*) and described (pp. 155, 156).

ANALYSIS 9

	Per cent
SiO_2	45.15
TiO_2	n. d.
Al_2O_3	18.90
Fe_2O_3	3.39
FeO	3.15
MnO	n. d.
CaO	17.77
MgO	7.94
K_2O	0.43
Na_2O	1.51
P_2O_5	0.99
H_2O+	0.24
H_2O-	0.28
Total	99.75

Analyzed by K. Willmann

REMOVAL OF THE SEDIMENTARY COVER

The intrusion of the andesite and consequent doming of the superjacent sediments may have been a slow process accompanied by contemporaneous erosion. To some extent, indeed, erosion may have proceeded almost *pari passu* with the uplift. The stages in the erosion would be largely those typical of other laccolithic domes, such as have been discussed by Jaggar[47] from the Black Hills of Dakota. Annular and radial valleys would develop speedily and the fault zones would be etched out into deep gullies. The material thus denuded would be redeposited unconformably upon the Sutter formation on the peripheral slopes of the dome, and would now be revealed by borings through the overlying andesite breccia. Within the andesitic core, once the sedimentary roof had been largely removed, the drainage would be determined by the irregular jointing and brecciated zones of the andesite, and was probably not unlike that which now exists. The sediments on the flanks of the laccolith were reduced to an irregular cone-surface, many parts of which may still be recognized beneath outliers of the andesite breccia. At this stage, the general form of the Buttes was perhaps not dissimilar to that of the Bear Butte laccolith in the Black Hills.[48] An earlier stage, before the roof of the laccolith had been denuded, was perhaps similar to the dome-shaped uplift west of Bear Butte or at Little Sundance Hill, where the igneous core is still concealed and the sedimentary cover is in process of being stripped.

Fortunately, at Marysville, we are able to gain a fairly accurate idea of the contours of the sedimentary beds immediately prior to the period of volcanic explosion, by a consideration of the distribution of the outliers of andesite breccia that rest upon them. Indeed, a study of these outliers reveals the impressive fact that the pre-volcanic surface of the sediments differed only slightly from their present surface; in other words, the sediments have only recently become exposed by the removal of parts of the overlying sheet of andesite breccia (see sections, figs. 4–9). It is of course only to be expected that the pre-eruption surface of the sediments should be similar to that of the sediments now exposed, for the present structures had already been impressed upon them by the laccolithic doming. Indeed, a close study of the outliers of breccia shows them to rest on a hummocky surface of the sediments, with annular and radial valleys closely similar to those of the present. Let us now consider in detail the occurrence of some of these outliers.

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[47] Jaggar, T. A., *op. cit.*, pp. 267–279, 1899–1900.

[48] Darton, N. H., The geology and water resources of the northern portion of the Black Hills, etc. U. S. Geol. Surv., Prof. Paper 65, pl. 16*B*, 1909.

Perhaps the most instructive outlier is that which rests upon the Chico (Cretaceous) sandstones, about a third of a mile from the steep side of the laccolith, south of South Butte. Here the breccia lies in an irregular hollow in the sediments and dips away from the laccolith at 30°. At a distance of a mile from the edge of the laccolith, on the farther side of West Butte Pass, the breccia rests on the Sutter formation and has an outward dip of only 10° or 12°. The breccia must once have been continuous across the intervening sediments, and it may reasonably be presumed that its dip diminished more or less regularly from 30° to 10° outward from the laccolith, for the crater from which the breccia was erupted lies near the center of the latter. Nearer the margins of the laccolith, the breccia has been wholly removed, but its dip must have continued to increase in that direction. If, then, the base of the breccia be restored in the areas from which it has been denuded, it is found to have reposed on a concave surface only slightly higher than the present crests of the sedimentary hills. This pre-eruption surface and its relation to the present topography are illustrated in the block diagram (fig. 5).

It is natural to suppose that the removal of the sedimentary cover from the top and flanks of the laccolith should have been facilitated by the existence of the radial and concentric fault zones, already mentioned. Considering their mode of origin, that is by the stretching and fracture of beds on a dome which rose as a result of pressures directed outwards from within, these fault zones must have gaped upwards, and thus have proved particularly susceptible to erosion. In some cases, indeed, it is clear that deep and narrow channels were carved along these zones prior to the eruption of the andesite breccia. An excellent example may be studied on the southeast flank of the laccolith. Here occurs a series of outliers of andesite breccia aligned along and on the sides of a north-south fault zone (fig. 11). This zone is partly bordered on the east by two large intrusions of rhyolite porphyry, of which the southern must have protruded 300 or 400 feet above the surrounding sediments at the time of the andesitic eruptions. For a mile from the edge of the laccolith, the fault-valley floor had an average gradient of about one in eight. Where it passed by the rhyolitic intrusions, the floor was littered with a talus of rhyolite blocks, for when the first torrents of andesite tuff and breccia poured down

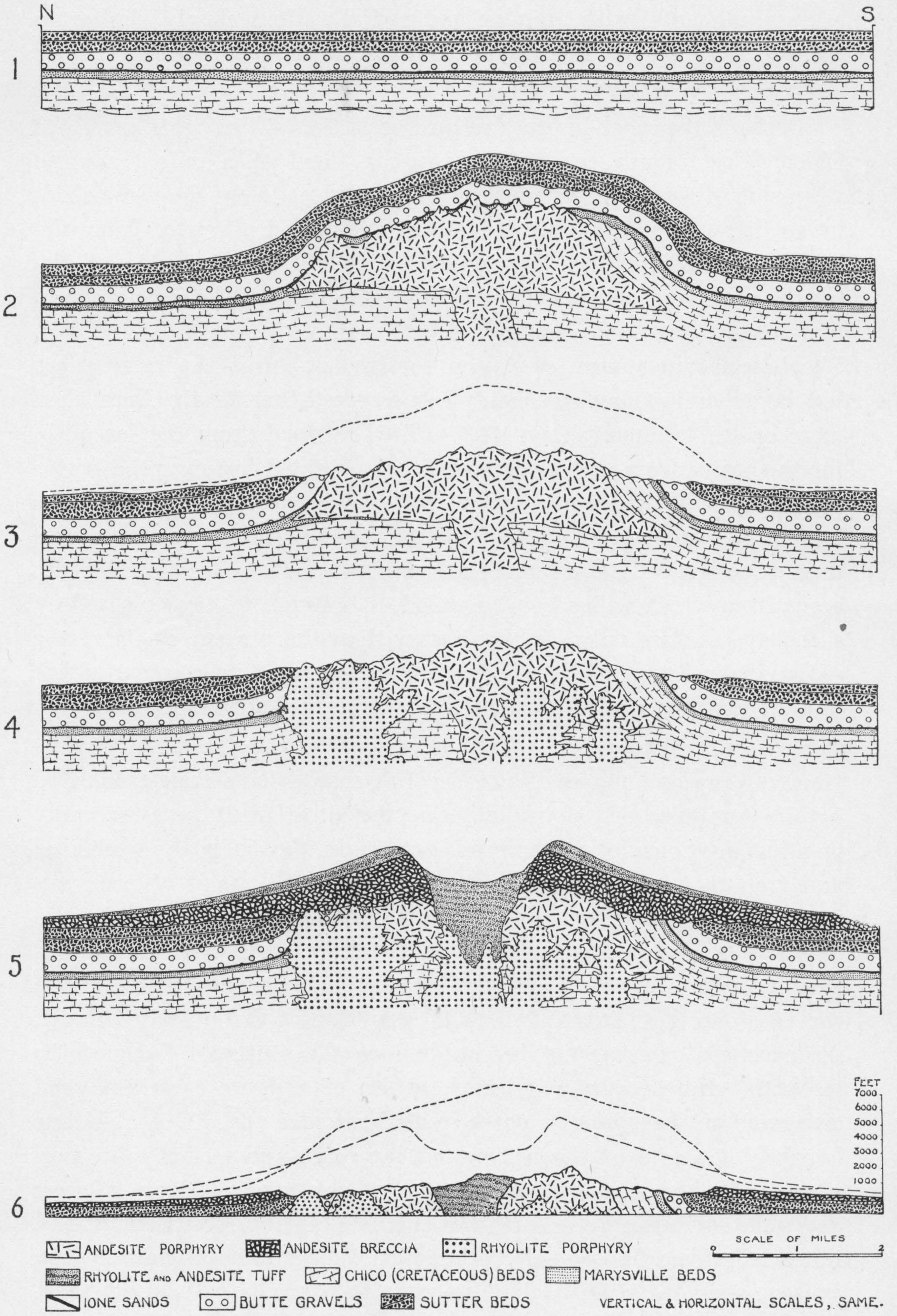

Fig. 10. Illustrating stages in the development of the Marysville Buttes. 1, original form of the sediments; 2, intrusion and doming; 3, denudation; 4, intrusion of rhyolite porphyries; 5, further rhyolitic intrusions and steam explosions forming a volcanic cone; 6, denudation to present form.

the valley they incorporated these blocks at their base and carried them to lower levels. Indeed, near de Witt's quarry, where the valley gradient was small, this mingled deposit of rhyolitic and andesitic blocks may be seen resting on the old valley-side, which rises eastwards at an angle of 30° to 35°, and shows a smooth, weathered surface of rhyolite (pl. 13*a*).

Other radial valleys, independent of fault zones, were cut into the sediments on the flanks of the dome by normal, consequent streams. Of these, two examples occur immediately to the northeast of the fault valley just described. These two valleys were separated by a high, narrow ridge, the present elevation of which is 900 feet, being indicated by the contact of the Sutter beds with the overlying andesite breccia. To the south of the ridge, the contact of these formations falls to an altitude of 700 feet within 300 yards; to the north, it falls to an altitude of 600 feet in 1000 yards, falling to 700 feet in the first half of that distance. Indeed, the two large valleys at present cut into the Sutter beds hereabouts appear to be following old channels that were eroded before the deposition of the breccias.

It is needless to discuss in further detail the form of the pre-eruption surface on the flanks of the laccolith; the reader may restore for himself a satisfactory picture by studying the distribution of the breccia outliers on the map and on the sections (figs. 4–9). Attention may be directed, however, to the former existence of a more or less concentric valley in the sediments to the west of West Butte. Approximately, this valley followed the course of the cart track indicated on the map. In places, it was almost three hundred feet deep. To the east of this old valley, between it and the margins of the laccolith, the presence of innumerable outliers of breccia points clearly to the fact that the present and pre-eruption surfaces of the sediments are almost identical (fig. 7). Indeed, we can trace the base of the breccia eastward across the sediments, noting the manner in which its outward dip increases, until it may be seen resting on the sides of the laccolith itself, dipping away therefrom at an angle of 70°.

To those who may examine the above evidence in the field, a word of caution may perhaps be permitted. Frequently one may observe loose piles of large andesite blocks littered over the surface of the sediments. These blocks are the residue of the andesite breccia left by the removal of the fine, tuffaceous matrix. The soft, underlying sediments are being rapidly eroded, so that the blocks are continually sinking, more or less vertically, to lower levels. In most cases, there-

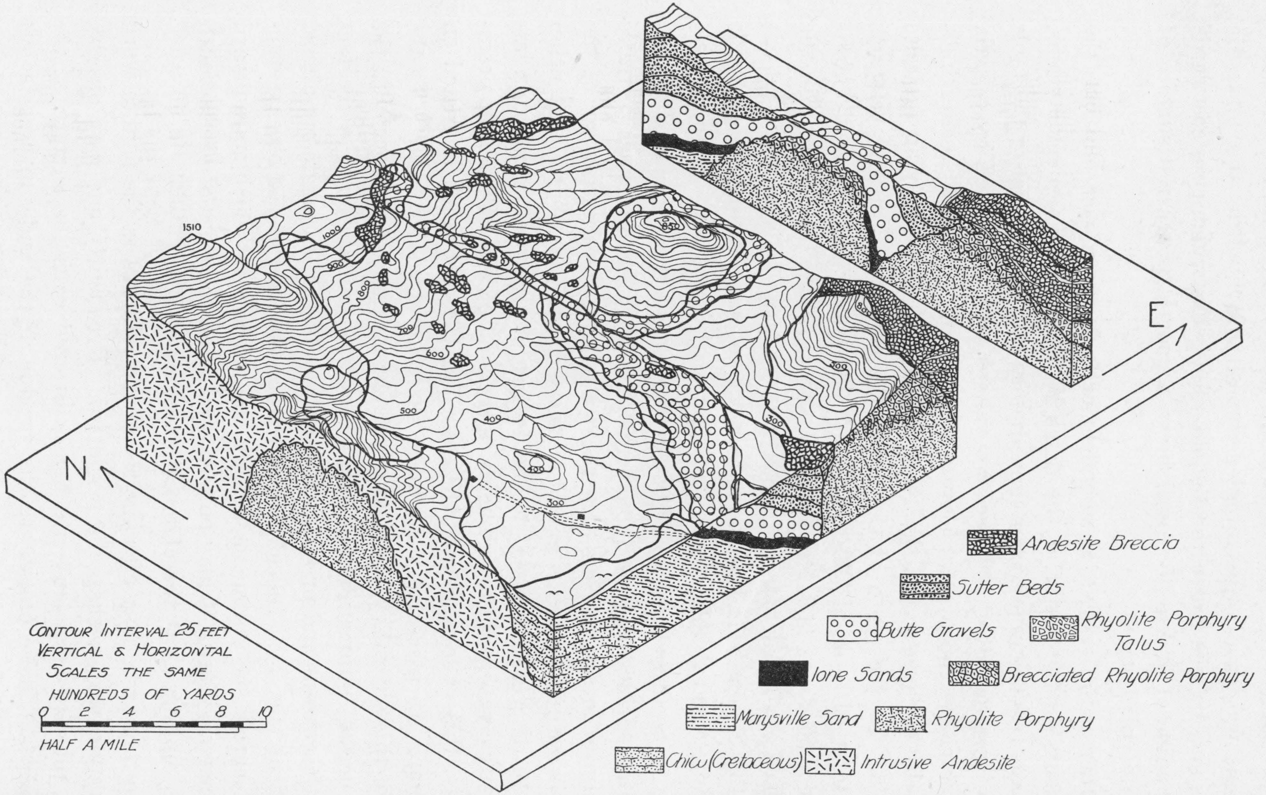

Fig. 11. Block diagram illustrating the structures adjacent to the southeast margin of the laccolith. Observe the distribution of the outliers of andesite breccia in relation to the north-south fault; also the doming of the Butte gravels and Sutter beds by the intrusion of rhyolite porphyry forming "850 Hill."

fore, the blocks now lie below their original positions, so that they must be ignored in any attempt to restore the form of the pre-eruption surface.

In view of the fact that the sediments on the flanks of the laccolith had been so deeply eroded prior to the eruption of the andesite breccias, it can hardly be doubted that the sediments which originally covered its top were also largely denuded before that event. The almost complete absence of sedimentary fragments among the andesite breccias erupted from the central crater in the core of the laccolith, is only explicable on the assumption that the sedimentary roof had been stripped from above the present site of the crater before the actual explosions.

THE ACID INTRUSIONS

Following the intrusion of the andesitic laccolith, but before the explosion of the bulk of the andesite breccias, a series of stocks or necks of rhyolitic character was injected into both the laccolith and the peripheral sediments. The latter had probably been eroded almost to their present level when this event took place; there is reason to suppose, moreover, that the intrusion of these rhyolitic masses initiated the explosion of the andesite breccias, as will be argued hereafter. The necks are clustered chiefly along the margins of the laccolith or have been punched through the adjacent sediments, but a few are wholly enclosed within the andesite. There is evidence also that there are concealed intrusions of these acid rocks below the laccolith, notably near its center.

While expressing some doubt, Lindgren was of the opinion that the rhyolitic rocks are intrusive into the andesites, but Dickerson erroneously considered them to represent the infilled vents from which much of the material constituting the Sutter formation was erupted (see p. 129).

The exposed form of the rhyolitic necks is typically that of a steep-sided dome of oval outline. In most of them, the longer axis approximates a quarter of a mile, but the largest intrusion is a mile in length and more than half a mile in width. By comparison with the surrounding sediments, the rhyolitic rocks are resistant to erosion and give rise to bold, craggy hills (pl. 11*b*). These hills are among the most conspicuous features of the Buttes, and are easily recognizable even at a distance by reason of the grayish white color of the rocks, which contrasts vividly with the chocolate brown tints of the andesites.

The sediments had already been upturned and faulted by the intrusion of the andesitic laccolith before the necks of rhyolite-porphyry were emplaced. It seems, indeed, that on the southeast flank of the laccolith, the presence of a north-south fault among the sediments partly determined the location of two of the rhyolitic masses, for their brecciated edges abut against it. In the sedimentary block south of South Butte, the rhyolite porphyry is seen to have insinuated itself among the beds in such a way as to deform their dip and strike near the contact. At a distance from the intrusion, the beds are disposed vertically and have a general east-west strike; traced toward the margins of the intrusion, the strike is suddenly deflected and appears to eddy round the mass, whereas the dip diminishes in places to about 20°. This change in the attitude of the sediments is most pronounced on the western side of the intrusion and is depicted in the block diagram (fig. 5).

The intrusion of the largest of the rhyolitic necks, that near the hamlet of West Butte, effected a serious disturbance of the structures which had been impressed upon the adjacent sediments by the original laccolithic doming. Previous to the invasion of the rhyolite porphyry, it is probable that the sediments dipped off the margin of the laccolith more or less regularly, the Cretaceous beds being in contact with the andesite and overlain by concentrically outcropping Tertiary beds. The intrusion of the rhyolite porphyry reversed this structure, so that the Cretaceous beds are now revealed as an almost continuous ring about the sides of the rhyolite. In addition, the beds on the eastern flank of the rhyolitic mass were so displaced that they now dip toward the margins of the andesitic laccolith.

Finally, the acid intrusion by Pugh Place, on the north side of the Buttes, and that forming the prominent "850 Hill," on the east side, arched the surrounding sediments in such a way that the Butte gravels are now upturned along their margins. These and similar structures suggest that many of the intrusive bodies spread rapidly beneath the surface, and that some of them may be united at a shallow depth, as suggested, for example, in the diagram (fig. 11). To produce such radical structural changes as those mentioned above, the rhyolite porphyries must have been extremely viscous at the time of intrusion. The general form of the masses and the absence of narrow, dike-like offshoots corroborate this view.

Lithology.—The rhyolite porphyry is usually a white or gray rock, or occasionally has a pale brown, blue-black, purplish, or lilac tint. The dominant type is plentifully studded with conspicuous, rounded phenocrysts of glassy quartz and feldspar and with deep brown foils of mica in a fine-grained, felsitic base. Within individual intrusions, the rocks exhibit a surprising uniformity. Flow-structure is almost always strongly developed, so that the rocks often present a decidedly platy aspect and tend to weather into large, thin slabs. On a small scale, this structure is accentuated by the flat-lying arrangement of the mica flakes along the flow-planes and by the manner in which they appear to have eddied round the phenocrysts of quartz and feldspar. The banding arises primarily, however, from the parallel orientation of alternate layers of more quartzose and more feldspathic material, the layers varying from a hair's breadth to 3 mm. in width. Similar banding is, of course, well known among acid volcanic rocks from many localities and has been discussed by the writer[49] recently from among certain Ordovician rhyolites in Wales. Among the Marysville rhyolite porphyries, the more feldspathic layers appear white and opaque, whereas the more quartzose bands have a dull, lead gray tint and a more glassy aspect. These parallel structures are attributed to the streaking-out of the material during crystallization, and to an unequal concentration of aqueous vapor along alternate layers during flow. The quartzose layers are believed, on this hypothesis, to represent those parts of the magma that were especially rich in water vapor and in which crystallization was thereby delayed, the feldspathic layers representing the drier fraction in which crystallization commenced at an early stage.

With few exceptions, the banding described above is disposed tangentially toward the margins of the rhyolitic necks. In the cores of some of the intrusions, however, this regular, concentric banding is replaced by a contorted banding that bears no definite relation to the intrusive margins and suggests rather the slow welling-up of a magma incapable of free expansion. Marginally, the banding is almost everywhere vertical or steeply inclined outwards, but occasionally it arches over toward the top of the necks, giving them a dome like form (pl. 11*c*). In the large intrusion near West Butte, the structure is more complex, there being minor domes on the sides of the main body.

The rhyolite porphyries do not always exhibit good flow-banding. Indeed, among those intrusions which occur within the laccolith, it is exceptional to detect any definite structure at all. These intrusions are singular also by reason of their paucity of biotite, their white, porcellanous character, and their irregular, more dike-like occurrence. In some places they are present as thin veins cutting the andesites but for the most part they are thoroughly decomposed and their precise relations cannot be determined. The relative ages of many of these porphyries and the biotite-rich, banded porphyries are unknown, but some of them appear to be contemporaneous. No satisfactory explanation can be offered here for the localization of the unbanded, porcellanous porphyries and the banded, mica-rich porphyries to the laccolith and to the sediments, respectively.

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[49] Williams, H., The Geology of Snowdon (North Wales). Quart. Jour. Geol. Soc., vol. 83, pp. 364–367, 1927.

Auto-brecciation.—A characteristic feature of many of the intrusions, particularly at their margins, is the presence of auto-brecciation. This structure is so well displayed among the Marysville porphyries and is so distinctive that a full discussion of the phenomenon seems warranted. Two types of breccia are distinguishable.

1. Bordering the pass that runs south from Pugh Place along the west side of North Butte, there are bold exposures of a brecciated rhyolite porphyry that consists of angular and subangular, banded porphyry fragments in a matrix of somewhat similar material. The fragments vary in size from blocks several feet in diameter to pieces that can hardly be discerned by the naked eye, and are assembled confusedly, the banding being oriented differently in adjacent fragments. The uniform and massive character of the matrix suggests that the fragments were incorporated immediately after or during solidification in a later intrusion of rhyolitic material; or, they indicate the auto-brecciation of a highly viscous intrusion, parts of which had solidified at an early stage. If the latter hypothesis be correct, then the structures may well be described as the product of flow-brecciation.

2. A second type of breccia, of much wider occurrence, and characteristically restricted to the margins of intrusions, appears to be due to a comminution of the rhyolite porphyry, perhaps partly during, but largely after solidification. In this type of breccia, the matrix is composed, not of massive rhyolite, but of pulverized material having a coarseness rarely exceeding that of gravel and usually as fine as sand. It resembles in this respect a true pyroclastic breccia. Occasionally, the brecciation is confined to regular layers, varying from an inch to about six inches in width separated by bands of massive rhyolite porphyry (pl. 10*a*).

The best localities for the study of this curious type of breccia are: (*a*) on the eastern edge of the intrusion that lies southeast of South Butte; (*b*) on the western edge of the "850 Hill" intrusion;

(*c*) on the southeastern edge of the large intrusion by the hamlet of West Butte; (*d*) in the deep, east-west gully to the north of De Witt's quarry, near Sutter City. Particular attention may be called to the last named locality (pl. 16*b*). Here an almost complete section is exposed across one of the intrusions. Of this section, the western end is composed of massive, well-banded porphyry. At the actual margin of the intrusion, the banding dips outward, that is westward, at about 35°; toward the interior, the banding becomes steeper and within the space of two hundred yards becomes vertical. From this point onward, however, the rhyolite porphyry is almost entirely and intensely brecciated. The breccia consists of angular and subangular fragments of banded porphyry up to 6 feet in length, but mostly 2 or 3 inches across, in a sand-like matrix of similar material. Occasional pieces of brown limestone and sandstone and of chert and other siliceous pebbles from the Butte gravels, up to 3 inches in length, are scattered throughout the matrix, but fragments of andesite are lacking. The breccia is entirely devoid of stratification. Toward the west, it merges gradually into the massive rhyolite porphyry. The breccia itself is also cut by dikes and stringers of porphyry, from three to eight feet wide, which are themselves fractured along their margins and pass by gradations into the breccia. The appearance suggests, indeed, that these thin dikes were in process of being fragmented.

Along the southeastern edge of the porphyry intrusion near West Butte, the breccia becomes increasingly coarse toward the interior. At the extreme margins, the porphyry is so intensely comminuted as to resemble a fine rhyolitic sand, and is intimately admixed with the buff sands and gray clays of the Marysville formation. In-

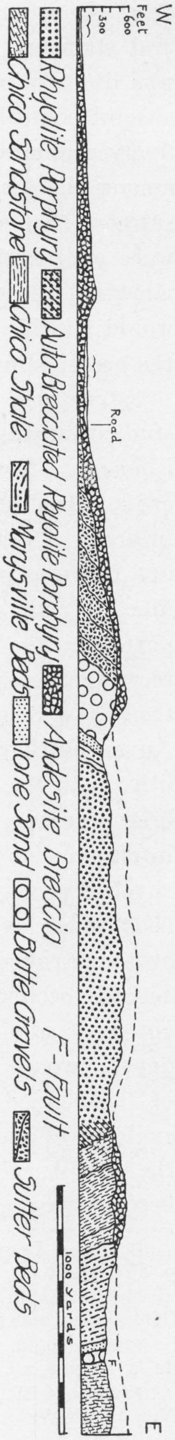

Fig. 12. Section near West Butte Village; the broken lines indicate the approximate form of the pre-eruption surface.

deed, the occurrence of the brecciated porphyry as irregular splotches and stringers among the Marysville beds suggests strongly that it was literally pumped into the sediments under high pressure and in a solid condition. The inference may perhaps be allowed that the finely comminuted porphyry was injected in the form of a hot mud among the loosely consolidated sediments. There is good reason to suppose that some, if not all of the Marysville porphyry intrusions were once highly charged with water vapor, and it seems that the marginal concentration of such vapor and its conversion into water would provide a mechanism adequate to explain the manner in which the breccias invade the adjacent sediments.

Structures precisely similar to those described above may be studied among the *pépérites massives* of the Auvergne and the Limagne. Those breccias are also notably free from stratification and are localized at the margins of intrusions. Most of them are intrusive into soft, Oligocene marls, and Michel-Lévy[50] considered them to be due to the expulsion of gases and of water from the margins of the dikes into the weak sediments. In this conception, he has been supported by the detailed work of Giraud[51] and of Glangeaud.[52] More recently, Benson[53] has described somewhat similar intrusive breccias from New South Wales. There the breccias are keratophyric; in the Auvergne they are chiefly basaltic, and at Marysville they are rhyolitic. At the first two localities, the sediments among which the breccias occur, were soft, light, and probably wet at the time of igneous intrusion. At the Marysville localities under discussion, the brecciated rhyolite porphyries were injected into the Sutter tuffs and Marysville beds under a shallow cover, and may indeed have reached the surface over restricted areas. If eruptions of rhyolite tuff and breccia actually occurred at the surface, the material would have been thrown out and admixed with sedimentary fragments, and the resultant deposit would probably have been stratified, much after the manner of the bedded *pépérites* of the Auvergne. There is now either no evidence of such rhyolitic eruptions, or the evidence is buried beneath the peripheral andesite breccias of the Buttes. The only rhyolitic breccias we see are clearly intrusive.

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[50] Michel-Lévy, A., Bull. des Services de la Carte Géol. de la France, t. 18, p. 859, 1890.

[51] Giraud, J., Études géologiques sur la Limagne (Auvergne). Bull. Soc. Géol. de la France, no. 87, t. 12, pp. 299–367, 1902.

[52] Glangeaud, Ph., Les régions volcaniques du Puy-de-Dôme. Bull. Soc. Géol. de la France, no. 123, t. 19, pp. 96–99, 1908.

[53] Benson, W. N., The geology and petrology of the Great Serpentine Belt of New South Wales. Proc. Linn. Soc. N. S. W., vol. 40, pp. 564–567, 603–624, 1915.

It is noteworthy that the Marysville rhyolite porphyries intruded under a deep cover or in contact with massive rocks, such as the andesites of the laccolith or the Chico sandstones, never exhibit intense brecciation of the *pépéritic* type, just as the basalt dikes of the Limagne are free from *pépéritic* aureoles where they are in contact with granites. This type of brecciation is characteristic of the top and sides of those porphyry intrusions which reached or almost reached the surface before solidification and were then in contact with incoherent sediments. Even along the margins of such shallow intrusions, however, the brecciation is irregularly localized, perhaps owing to an unequal concentration of aqueous vapor in the porphyries during injection. Benson has described the process of intrusion of the Australian keratophyre breccias thus:

> Though the ascending magma must have been rapidly chilled by the wet sediments, it must also have been charged with a considerable amount of water, from which it could not free itself. . . . . The movement of the molten material below would break up the crust as it consolidated, and it would also be shattered by the strains produced in the necessarily rapid variations in temperature, so that, above the level where the crystallization took place, the comminuted igneous material would move forward in the form of a watery slurry or mud. This mud would escape from the vent in which it rose, by the path of least resistance, which, under a considerable overburden of silt and sea-water, might sometimes be by intrusive injection into the surrounding partially consolidated sediments, at other times, by breaking through and discharging into the sea.

This interpretation is essentially that which is here offered for the rhyolitic breccias at Marysville. It is probable that both the Sutter and Marysville beds were poorly compacted at the time of the intrusions. Moreover, the manner in which the rhyolite porphyry fingers and grades into the breccia suggests that molten material was being urged upwards during and after the formation of the brecciated crusts. There is no indication that the intrusions were attended by lava flows, nor indeed that rhyolitic material ever reached the surface in a molten condition. Quick chilling, increase of vapor tension by crystallization, the violent expansion of steam, and the vibrations set up in the crust by the movement of molten material within, these are processes which appear adequate to explain the observed brecciation. The sediments may have had a high water-content and so have contributed to the formation of steam, but such a contribution is not demanded by the present hypothesis: the magma itself may well have contained a sufficient proportion.

Microscopical petrography.—The rocks to be described below have thus far been designated rhyolite porphyries. On certain grounds, some of them might be more accurately classified as quartz porphyries; on other grounds, some of them present so striking a resemblance to effusive rocks, both in the field and under the microscope, that the term intrusive rhyolite might be applied to them with reason.

The rocks belong essentially to two types, distinguishable, respectively, by the paucity or abundance of biotite, and by the presence or absence of conspicuous flow-structure. Both types may occur within the same intrusion; in such cases, they were probably injected more or less at the same time, since they grade almost imperceptibly into one another. Apart from these variations, the rhyolite porphyries are remarkably uniform in character, and were thoroughly differentiated prior to intrusion.

Briefly, the dominant rock consists of a micro- to crypto-graphic, granular, felsitic base, showing fluxion-structure and enclosing abundant flakes of deep brown biotite, together with phenocrysts of feldspar and less commonly of quartz, and accessory apatite. Of the porphyritic constituents, quartz occurs in rounded and broken, pyramidal forms, averaging 2 mm. in length. Although many of the phenocrysts are corroded, the absence of corrosion-borders suggests that the crystals were resorbed before the matrix commenced to solidify and were floated to their present position only when the interstitial melt was unable to affect them. Several of the crystals are traversed by irregular and perlitic cracks, possibly due to strains set up by the quick chilling of the matrix. Occasionally, angular and crescentic chips of quartz thus detached are seen to have been floated away from the parent phenocrysts.

Among the porphyritic feldspars, acid plagioclase usually exceeds orthoclase in amount. The crystals are tabular or well rounded, and, for the most part, range from 1 to 2 mm. in length. The plagioclase varies from almost pure albite to acid andesine, a basic oligoclase being the dominant variety. Both the plagioclase and orthoclase are generally well zoned.

Biotite is developed as minute inclusions within the porphyritic feldspars and as larger flakes oriented along the flow-planes of the matrix. It is usually of a brownish black color in hand specimens, but often appears greenish under the microscope, and has the following pleochroic schemes:

X	*Y* and *Z*
Light yellowish green	Chestnut to deep reddish brown
yellowish brown	black
	chocolate brown

The darker brown varieties have an optic axial angle, $2V$, of 5° to 10° and a refractive index, α, 1.63. They appear to be ferriferous varieties, poor in magnesia.

Apatite is invariably present, and may be so abundant as to merit classification as an essential constituent. It occurs in stumpy prisms, from three to four times as long as broad, both as inclusions in the phenocrysts and scattered haphazard throughout the base. In some slides, the apatite constitutes as much as 3 per cent of the bulk. Occasionally, it encloses minute grains of zircon.

The matrix of the normal rhyolite porphyries rarely shows the banding of more quartzose and more feldspathic layers so distinctly under the microscope as in the field. It appears as a micro- to cryptogranular mosaic of quartz and feldspar, sprinkled with magnetite dust and carrying abundant microliths of orthoclase and acid plagioclase, mostly from .025 to .040 mm. in length. Perlitic and spherulitic textures appear to be absent, and there is no definite evidence that the matrix was ever glassy. The feldspar microliths are occasionally arranged parallel to the fluxion-banding and may be so plentiful as to give the rocks a trachytic aspect: in other sections, the microlithic areas alternate with layers of quartz-feldspar mosaic. In such mosaics the feldspar is commonly disposed poikilitically toward the quartz. A patchy appearance may be given to the matrix by the segregation of magnetite dust and ferruginous pigment or of minute, bright red and green globulites. Clear, irregular streaks of quartz mosaic probably represent areas infilled with residual, excess silica (see pl. 18, *b, c*).

Exceptionally, the rhyolite porphyries are partly glassy. An analysis of such a glassy porphyry shows that it differs from the normal porphyries described above chiefly in its high content of combined water.

Among the auto-brecciated rhyolite porphyries on the western side of North Butte, perhaps the most noteworthy feature is the trachytic appearance of many of the fragments, which consist of densely crowded microliths of biotite, albite, oligoclase, and orthoclase, indicating a much more advanced stage of crystallization than is witnessed in the normal porphyries. The individual fragments of the breccias are sharply defined. The matrix in which the fragments lie is poor in microliths, being essentially a cryptofelsite heavily stained with limonitized granules of magnetite and intensely fractured.

The *pépéritic* type of breccia presents many unusual characters, but is especially marked by the decomposition of its biotite. The porphyry fragments exhibit opaque, white, porcellanous crusts, from one-eighth to one-quarter inch thick, that pass inward gradually to unaltered rock containing fresh biotite. This breakdown and disappearance of the biotite in the porcellanous crusts is probably due to a reheating and oxidation by hot solutions. The white porphyry fragments stand out conspicuously in a gray, soft, chalk-like matrix, and are disposed without definite orientation. Viewed under the microscope, the decomposition of the biotite is seen to be accompanied by the separation of clouds of iron ore in formless granules and dust. The groundmass of the porphyry, which is normally clear, becomes gray or even black, and appears milky white or pale brown by reflected light, as if the iron ore were titanomagnetite. Occasionally, the porphyritic feldspars are wholly replaced by magnetite dust; elsewhere, the dust is unequally concentrated in layers that probably follow the original flow-planes of the porphyry. Chloritic matter appears to be absent. The matrix between the porcellanized fragments consists primarily of a clear, micro- to cryptocrystalline mosaic of quartz and untwinned feldspar. It is apparent that much, if not all of this fresh matrix crystallized slowly about the porphyry fragments when they were already solid, for the mosaics of the matrix present textures that vary in definite relation to the inclusions, both as to form and coarseness. Compared with the inclusions, the matrix is notably poor in iron oxides and is also devoid of biotite. It is also remarkable for the presence of abundant angular pieces of quartz. The angularity of these quartz fragments contrasts strongly with the rounded and embayed forms of the quartz in the porphyries, and hints at derivation from some other source. It may be that the angular quartz grains represent particles of sediment carried up by solutions during and after the brecciation of the porphyry, for they are often associated with recognizable sedimentary pebbles.

The hydrothermal alterations of the *pépéritic* breccias, mentioned above, attract attention by the complete absence of kaolinization and micacization of the feldspars and of pyritization. The changes are almost restricted to the decomposition of the biotite and consequent liberation of iron ores, the red color of many of the breccias being due to subsequent oxidation of the iron. In many respects, the breccias recall the keratophyre breccias described by Benson[54] from New South Wales.

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[54] Benson, W. N., *op. cit.*, p. 569, 1915.

It remains now to discuss briefly the rhyolite porphyries intrusive into the andesitic laccolith. These are generally typified, as already stated, by the absence of conspicuous flow-banding and by the paucity of biotite. They resemble white porcellanites and break with a hackly fracture, when their surfaces are seen to be pitted from the decomposition of the porphyritic feldspars, the cavities being lined with rusty iron oxides and brown carbonates. Microscopically, these porphyries are characterized by:

a. the presence of green biotite, instead of the brown varieties common to the normal porphyries;

b. the segregation of magnetite dust into more or less circular spots, averaging 0.15 mm. in diameter.

c. the decomposition of the matrix, with the development of abundant sericite, kaolin, and calcite.

This intense decomposition of the porphyries intrusive into the laccolith is in marked contrast to the freshness of the massive porphyries intrusive into the sediments. The former have suffered considerable hydrothermal alteration, and it may not be fortuitous that such alteration of the porphyries is most intense where they invade the propylitized facies of the andesites. The segregation of dusty iron ores in the porcellanitic porphyries resembles that observed in the *pépéritic* breccias, and may also be attributed to hydrothermal action. It is possible that some of the green biotite was originally brown, but for the most part it appears to be primary. Instead of being platy as in the normal porphyries, the biotite in the porcellanous types is developed in tufted, more or less fibrous habits. It is sometimes chloritized and is then attended by granular magnetite, titanite and rutile. The breakdown of the porphyritic feldspar to calcite and mica is occasionally accompanied by the development of clearer acid and alkaline varieties. Porphyritic quartz is rare and may be lacking, a phenomenon seldom observed in the normal porphyries.

Chemical composition.—The biotite-rich rhyolite porphyries are, as might be anticipated from the preceding descriptions, notably alkaline. The following analyses (10 and 19) of a typical specimen from de Witt's quarry, near Sutter City, and of a glassy rhyolite from the intrusion west of North Butte, show that soda and potash are present in almost equal amounts. This condition differs markedly from that observed in the Tertiary rhyolites of the Sierra Nevada, for in them potash is usually far in excess of soda. The silica percentage of the normal, biotite-rich porphyry at Marysville (10) agrees closely, however, with the average silica percentage of nine Sierran rhyolites (71.27), though both the lime and magnesia content of the former are much higher than in the latter. The normative content of quartz in the Marysville rock is about 26.5 per cent; that of the feldspars is as follows: orthoclase, 22.8; albite, 33.0; anorthite, 12.0 per cent. In the mode, however, the plagioclase must be in much greater proportion to the orthoclase owing to the abundance of biotite. Below are given a number of analyses of Sierran rhyolites for purposes of comparison. Concerning the glassy rhyolite (analysis 19), the most noteworthy feature is its high content of combined water. Indeed, this water-content is much higher than that quoted by Rosenbusch for any of the liparite-obsidians. The average of four analyses of pitchstone quoted by Rosenbusch[55] gives a water-content of 5.13, and of liparite-pumices, 3.05. The significance of this high water-content in the Marysville porphyry will be discussed at a later stage; here it may be suggested that such a richness of water may account for the prominent flow-banding of the rocks and for the violent steam explosions which accompanied their intrusion.

	10	11	12	13	14	15	16	17	18	19
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
SiO_2	71.20	73.23	71.39	72.70	70.64	71.21	69.45	71.85	69.99	67.93
Al_2O_3	14.96	12.73	14.13							15.01
Fe_2O_3	1.10	0.99	0.63							1.29
FeO	0.42	0.16	0.37							0.20
MnO	Trace	Trace	Trace							Trace
TiO_2	0.12	0.09	0.17							0.21
CaO	2.75	0.61	1.01	1.15						2.03
BaO		0.02	0.09							
MgO	0.62	0.22	0.08							0.51
K_2O	3.88	5.17	5.69	4.81		4.16	5.25	5.11		3.93
Na_2O	3.90	1.91	2.89	.46		1.82	0.80	1.48		3.76
H_2O-	0.20	0.53	0.42							0.71
H_2O+	0.55	4.51	3.32							4.33
P_2O_5	0.15	0.02	0.03							0.12
S	Nil									
CO_2	Nil									
Cl	Trace									
Totals	99.85	100.19	100.22							100.03

10. Biotite-rich rhyolite porphyry, de Witt's quarry, three miles northwest of Sutter City, Marysville Buttes. Analyzed by W. H. Herdsman.

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[55] Rosenbusch, H., Elemente der Gesteinslehre, ed. 4, p. 359, 1923.

11. Rhyolite, Amador County, Sierra Nevada. Analyzed by W. F. Hillebrand, quoted from H. W. Turner, Jour. Geol., vol. 3, p. 407, 1895.
12. Rhyolite, Plumas County, Sierra Nevada. Analyzed by W. F. Hillebrand, quoted from H. W. Turner, *loc. cit.*

13, 14. Rhyolites, Plumas County
15, 16, 17. Rhyolites, Amador County
18. Rhyolite, Calaveras County
Analyses chiefly by W. F. Hillebrand, quoted from H. W. Turner, Fourteenth Ann. Rept., U. S. Geol. Surv., pt. 2, p. 487, 1892–93.

19. Banded, glassy rhyolite; intrusion west of North Butte, Marysville Buttes. Analyzed by K. Willmann.

THE EXPLOSIVE PHASE

The andesitic laccolith had been largely stripped of its sedimentary cover when violent steam explosions issued from a central crater in its core and from minor, lateral craters at and near its margins. This type of volcanic eruption, involving the disruption of an early intrusion by steam explosions, although apparently unusual, is not unknown elsewhere. A few examples will suffice. Thus, Branco[56] elaborated the suggestion made by Suess that the well-known Riesskessel explosion was phreatic in type and followed upon a laccolithic injection which had domed the superjacent granite and sedimentary cover. Branco and Fraas[57] have described similar eruptions from the Steinheim basin, and recently Soellner[58] has discussed the origin of certain breccias due to the blasting of a vent through the core of a domelike intrusion of essexite-gabbro in the Kaiserstuhlgebirges, near Breisach, Baden.

The immediate cause of the steam explosions at Marysville is a matter for conjecture. It is certain, however, that no fresh magma was erupted, for the ejecta are confined to fragments of previously consolidated rocks blown out at a comparatively low temperature. In seeking for the source of the steam, two possibilities suggest themselves, namely, a magmatic source and ground-waters heated in depth. The potency of ground-waters to produce violent steam explosions under certain conditions is generally recognized and was exemplified on a grand scale in the Kilauea eruptions of May, 1924.[59] Such an agency, however, is hardly likely to have caused the eruptions at Marysville, which issued chiefly from a vent located in the core of the solid laccolith and surrounded by a belt of andesite from one to two miles wide. It is more reasonable to suppose that the steam emanated from fresh magma intruded beneath the laccolith. Of recent years, emphasis has been laid, particularly by the members of the Geophysical Laboratory at Washington, on the rôle of vapor tension in crystallizing magmas as a primary cause of volcanic eruptions. There can be little doubt that if we postulate a series of intrusions of fresh magma below the solid laccolith, we thereby provide a mechanism that is adequate to explain the violence and repetition of the steam explosions at Marysville. It has already been shown that the rhyolite porphyries which occur among the sediments on the flanks of the laccolith were intruded after the beds had been folded and faulted by the laccolithic disturbance; some of them must have been intruded under a shallow cover, when the sediments had been eroded almost to their present level, that is, immediately before the explosion of the andesite breccias. It is possible, indeed that many of the intrusions actually accompanied the explosions. Moreover, the occurrence of several small outcrops of rhyolite porphyry within the laccolith and the presence of porphyry fragments among the explosive ejecta from the central crater, make it clear that acid intrusions are plentiful beneath the andesitic cover. Since some of the intrusions of rhyolite porphyry immediately preceded the steam explosions, and since some of them may well have been contemporaneous, is it not possible that the explosions may have been a direct result of the intrusions? There is an additional reason for believing that the explosions were causally connected with the intrusions in the fact that the latter were originally very rich in water vapor and probably emitted sufficient steam to account for the explosions. For example, the quickly chilled, glassy rhyolite porphyry near North Butte contains 4.33 per cent of combined water. That the explosions were at first paroxysmal indicates that pressures had long been accumulating beneath the laccolith, just as they would increase during the slow crystallization of an underlying magma. There were many subsequent explosions of tuff and breccia, and sufficient time elapsed between some of the explosions for the erosion of deep valleys in the earlier ejecta (pl. 14*b*). From this, it may be presumed that material continued to be intruded and to crystallize in depth throughout a long period, generating high vapor pressures, relieved at irregular intervals by eruption. Such a process has been invoked to explain the repeated explosions of the *nuées ardentes* from

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[56] Branco, W., Abhand. Kön. Preuss. Akad. Wissensch. Berlin, p. 14, 1902.

[57] Branco, W., and Fraas, E., Abhand. Kön. Preuss. Akad. Wissensch. Berlin, p. 21, 1905.

[58] Soellner, J., Zur Petrographie und Geologie des Kaiserstuhlegebirges im Breisgau. Neues Jahrb. f. Min., Geol., u. Pal. Beil., Bd. LV, Abt. A, pp. 299–318, 1927.

[59] Stearns, H. T., The explosive phase of Kilauea Volcano, Hawaii, in 1924, Bulletin Volcanologique, Naples, 1926.

Mont Pelée in 1902,[60] and is in accord with the work of Morey[61] on vapor tension in magmas. The absence of essential ejecta, that is, of fragments of fresh magma, bombs, scoria, and so forth, among the products of the Marysville volcano, cannot be assumed to inhibit the idea of such a process. The intermittent explosions at Marysville are thus considered to be more or less analogous in origin to the explosions of Lassen Peak in 1914–1915. Of the latter, Day and Allen[62] have written:

> If the explosions had been due only to water from without, pouring into rifts in the crater floor, and exploding as steam on reaching the hot zone, no such periodicity . . . . would have been possible. Considering the explosions to be due to a more or less regular release of water vapor from a crystallizing magma, to which any outside water is merely contributory, then explosions might be expected to occur as often as the accumulating pressure within overcomes the resistance of the envelope.

The steam eruptions of the Marysville volcano were *ultra-vulcanian,* in the sense defined by Mercalli, that is the ejecta were entirely lithic.

FORM OF THE VOLCANO IMMEDIATELY BEFORE THE EXPLOSIONS

It has already been remarked that the sedimentary ring encircling the andesitic laccolith was denuded almost to its present elevation prior to the volcanic episode. It formed a more or less cone-shaped surface, with an average slope of about 10° near its base and steepening toward the laccolith. This surface was cut by concentric valleys following the weaker strata, and by radial, consequent valleys, some of which were incised along zones of faulting. Above the sediments, projected necks of rhyolite porphyry. The laccolith itself was in most places steep-sided, and probably reached an elevation of about 3000 feet. On its northern side, it presented craggy faces at least 1300 feet high, of which the lowest 300 feet were vertical cliffs. The western face of the laccolith was also steep; at one place, the pre-eruption surface may be seen beneath a thin veneer of andesite breccia and dips outward at 70° (fig. 4). The southern and eastern sides of the laccolith sloped at lesser angles. Resting on the top of the laccolith, there were residual outliers of the sedimentary cover, but these were probably confined to the peripheral parts. Other features of the pre-eruption surface have previously been discussed (*ante,* pp. 158–163).

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[60] Shepherd, E. S., and Merwin, H. E., The gases of Mont Pelée. Jour. Geol., vol. 35, pp. 97–116, 1927.

[61] Morey, G. W., Development of pressure in magmas. Jour. Washington Acad. Sci., vol. 12, pp. 219–230, 1922.

[62] Day, A. L., and Allen, E. T., The volcanic activity and hot springs of Lassen Peak. Carnegie Inst., Washington, Publ. 360, p. 79, 1925.

CHARACTER OF THE EXPLOSIONS

The main explosions that gave rise to the great mass of andesite breccia forming the lower slopes of the Marysville Buttes, issued from a more or less cylindrical vent blasted through the center of the laccolith (fig. 13). The general form of this vent, now clogged by the tuffs of the final explosions, recalls the cylindrical, breccia-filled pipes so plentifully drilled through the Keuper and Jurassic beds of the Schwabian Alps. These pipes or diatremes have been fully described in Branco's classical work,[63] and were attributed by him to gas explosions emanating from a concealed laccolith. Similar pipes, infilled with tuff, breccia, and agglomerate are extremely abundant in the Central Valley of Scotland and are so intimately connected with intrusions of dolerite that a causal relation may reasonably be affirmed. Thus, Daly[64] reviewing Geikie's detailed studies of these Scottish volcanoes, writes:

> Gas emanations from the magma forming these actual intrusives or similar ones occurring in the underlying pre-Carboniferous formations, together with the possible emanation of gas from the heated country-rock, would seem to be competent to explain most of the tuff-necks. Explosive drilling (diatremes) and gas fluxing might in turn dominate in the opening of vents.

Daly also cites the recent eruptions at Usu-san, Japan, as other examples of explosive activity due to concealed, satellitic intrusions. The tilting of the land and the opening of 45 new craterlets near Usu-san are both attributed to magmatic injection not far below the surface. Many of the vents blasted through the Devonian sediments of the Siebengebirges,[65] and the craters of the Eifel, Germany, are further illustrations of the effects of steam explosions. It has been suggested that at Marysville, the cause of the volcanic eruptions was the accumulation of vapor tension consequent upon the intrusion and crystallization of rhyolite porphyries beneath the andesitic laccolith. The precise *modus operandi* of the gases in the formation of the crater at Marysville is, however, a matter of doubt. It is indeed the problem that presents itself at many volcanoes, namely, as to the manner in which cylindrical vents can be drilled through great thicknesses of rock. It is probable, as Daly[66] has suggested, that many such vents are formed "by the continued passage of the blowpiping gases, by the mechanical erosion of the walls by outflowing lava, or by the piecemeal stoping of the walls by the lava column," but at Marysville no fresh lava ever reached the surface, nor do the andesitic ejecta from the crater exhibit even a trivial fusion. Clearly, the Marysville, vent was not formed by any fusing, blowpipe action. It is equally clear that the present form and dimensions of the crater are not the result of a single explosion, but of a long series of eruptions. The first steam explosions may have issued from a narrow fissure that widened in depth. Such a fissure may have been enlarged partly by the actual violence of the later explosions and partly by the heating and fracturing of the wall-rocks. Detached blocks falling into the vent between successive eruptions and hurled upwards by steam under high pressure would provide powerful tools for the widening of the crater. In a similar manner, ejecta falling back into the crater during an eruption and being repeatedly thrown out by the ascending steam would aid materially in widening the aperture. The power of steam under pressure to effect such destruction cannot be denied when it is recalled that a large part of the mountain of Bandai-san, Japan, was decapitated by simple steam explosions,[67] and that the great explosions at Tarawera, New Zealand, were also phreatic in type.

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[63] Branco, W., Schwabens 125 Vulkan-Embryonen. Stuttgart, 1894.

[64] Daly, R. A., Igneous rocks and their origin, pp. 298–300, 1914.

[65] Laspeyres, H., Das Siebengebirges am Rhein. Verhand. des Naturhist. Vereins d. Preuss. Rheinl. u. Westf., Bd. 57, 1900.

[66] Daly, R. A., *op. cit.*, p. 253.

CHARACTERS OF THE PERIPHERAL EJECTA

By far the greater part of the fragmental andesites that build the lower, gently-dipping slopes of the Buttes were erupted from the central vent referred to above. During the eruptive period, there were many violent explosions, by which angular boulders up to fifteen feet in length were thrown out, and these explosions alternated with others that yielded only fine-grained tuffs. Between the explosions, streams were cutting channels on the flanks of the cone. Such a channel may be seen, for example, on the south side of "1000 Hill," one and a half miles southeast of North Butte. It is cut into fine tuffs and is occupied by coarse breccias (pl. 14*b*). Similar channels are common among the so-called "andesitic mud flows" of the Sierra Nevada.[68] During these intervals of erosion, also, much of the finer ejecta was rounded by water-action and appears now as volcanic sand and gravel. This irregular intensity of the explosions and the intervals of erosion, explain many of the features of the pyroclastic deposits. Fine, sand-like tuffs, gray or buff in color, alternate with bands of lapilli tuff and coarse breccias, and are occasionally divided by thin lenses of detrital tuffs. The remarkable uniformity and thinness of some of the beds suggest that the material was washed slowly into place. Generally, the finer the tuff the more pronounced is its bedding, and, except on a large scale, the beds of coarse breccia, usually from six to ten feet thick, show little or no stratification within themselves, presenting rather a chaotic admixture of fragments of all sizes.

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[67] Sekiya, S., and Kikuchi, Y., The eruption of Bandai-san. Jour. Coll. Sci., Tokyo, vol. 3, pp. 91–172, 1890.

[68] An excellent example occurs one and one-half miles north of Vallecito, one-third of a mile west of the road to Murphys (Big Trees Quadrangle).

With rare exceptions, the ejecta are of andesitic character; they are indeed nothing but comminuted fragments of the andesitic laccolith. Occasionally, pieces of rhyolite porphyry and of sediment may be found, but it must be emphasized that these are extremely rare and are almost confined to the lowermost, earliest ejecta. Vesicular and scoriaceous ejecta, lava-drops, bombs deformed during flight, and similar products typical of the eruption of fresh magma are here conspicuously absent. The coarser ejecta belong to the category of cognate lithic blocks;[69] the finer ejecta are crystal and lithic tuffs, in part detrital. The maximum size of the blocks is about 15 feet across, and it is noteworthy that there is no regular variation in the size of the fragments as they are traced away from the vent. By the removal of the fine, tuffaceous matrix, the large blocks are left strewn on the surface, and give a characteristic appearance to the lower slopes of the Buttes, as represented in the photograph (pl. 13*b*).

Evidence will be offered hereafter for considering that the ejecta were erupted at a comparatively low temperature. Careful search has revealed only a few blocks that show even a crude ''bread-crust'' surface. Lacroix[70] and others have shown that ''bread-crusting'' may result from the superficial heating of previously consolidated rocks. The rare ''bread-crusted'' blocks among the Marysville breccias are traversed by narrow and sharp, U-shaped cracks, from one-half to one inch wide, and up to three inches deep. In shape, these cracks resemble those described and figured by Lacroix from among the ejecta erupted in an almost solid condition from Mont Pelée in 1902. They contrast strongly with the widely gaping cracks typical of viscous bombs. It will be noted later that a microscopical examination of the exterior of one of the Marysville ''bread-crust'' blocks fails to reveal any fusion of the constituent minerals, and thus indicates the low-temperature character of the eruptions. The complete absence of decomposition in most of the ejecta, other than that resulting from oxidation, reheating and subsequent weathering, and the absence of chemical precipitates, sulphates, and so forth, among them and on the sides of the crater, suggest that water and perhaps also carbon dioxide were the only volatile ingredients present during the explosions. Solfataric activity seems to have played no part either during or after the eruptions.

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[69] Definitions of the writer, Notes on the characters and classification of pyroclastic rocks. Proc. Liverpool Geol. Soc., vol. 14, p. 230, 1926.

[70] Lacroix, A., La Montagne Pelée et ses éruptions, pp. 522–527, 1904.

Mode of Deposition of the Andesitic Breccia and Tuff

Lindgren[71] described the andesitic ejecta as "mud lavas" and considered that "they probably poured out as a semi-fluid, hot mud, and were only to a less extent the result of ash showers." The Marysville deposits present such a striking resemblance to many of the fragmental andesitic deposits of the Sierra Nevada that a common mode of formation may confidently be asserted. Of the Sierran rocks, the work of the U. S. Geological Survey makes it clear that they are, at least in part, the products of so-called "mud flows." Turner[72] describes them as follows:

> The fragmental lava appears to have been mixed with water, perhaps derived from melting snow at or very near the sources of the eruption. But however these mud flows were formed, on their course down the slopes of the range they caught up much foreign material. . . . . Along the east side of the Great Valley of California these andesite tuffs grade into well-stratified material containing abundant rolled sand grains, and such beds may be regarded as water deposits. . . . . There is excellent evidence that most of the sources of eruption in the Sierra Nevada were along the crest of the ridge, and that the fragmental material was transported from these sources to the border of the Sacramento Valley, a distance of about 50 miles, on a comparatively gentle slope.

He compares the Sierran deposits with those produced during the famous eruption of Bandai-san, Japan, in 1888. Sekiya and Kikuchi,[73] referring to the description of others that the products of the eruption were essentially "mud streams," emphasize the fact that Bandai-san was not a true mud volcano, but that the mud resulted from admixture of the ejecta with water after eruption.

> Moreover, as far as our prolonged examinations went, there was no evidence of any discharge of mud from beneath. It is true that in the Nagase Valley and

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[71] Lindgren, W., U. S. Geol. Surv., Marysville Folio, no. 17, 1895.

[72] Turner, H. W., Further contributions to the geology of the Sierra Nevada, Seventeenth Ann. Rept. U. S. Geol. Surv., pt. 1, pp. 537–538, 1895–96.

[73] Sekiya, S., and Kikuchi, Y., Cited by Turner, H. W., *op. cit.*, p. 539, 1895–96.

> other places there are now immense quantities of mud, but these became mud only after the eruption. During its descent, for example, a part of the debris, mingling with the waters of ponds and lakes in its course, doubtless acquired a muddy character and was thus assisted in its flow; and, again, that which reached the stream of the Nagase-gawa became admixed with sufficient water to thin it to the consistency of a paste. But by far the greater volume was in a comparatively dry state, being moistened only by the condensing steam, and must have derived its fluid or semifluid properties from a rapid process of pulverisation. . . . . It is manifest that the immediate cause of the eruption was the sudden expansion of steam pent up within the mountain. Of lava or pumice there is no trace. The gray-colored ashes, which form a chief product of the explosion, are evidently the powder of preexisting rocks decomposed by the action of fumaroles, and have not been derived from fused magma.

A somewhat similar explanation has been offered for the devastating ''mud flows'' that attended the eruption of the Tokachidake Volcano, Hokkaidô, Japan, in 1926[74]

Such a mode of origin also offers a satisfactory explanation for many of the features of the Sierran and Marysville andesitic deposits.

On a large scale, the ejecta of the Marysville volcano are prominently stratified, but closer examination shows that many of the individual beds consist of unassorted fragments of widely different coarseness. The coarser beds in particular are poorly sorted, whereas the finer tuffs are usually well bedded. These characters are common to pyroclastic material ejected onto the sides of many other volcanic cones. They are typical, for example, of many of the tuffs of the Soufrière[75] and Mont Pelée eruptions of 1902[76] Although the ejecta of a single eruption may be wholly unassorted, those of successive explosions together produce a distinct stratification.

At Marysville, it is possible to distinguish three types of pyroclastic rocks, namely:

a. coarse ejecta, showing a chaotic assemblage of blocks of very different sizes in a finer matrix;
b. fine tuffs and lapilli tuffs, generally stratified;
c. bedded volcanic sands and gravels.

These three formations are irregularly interbedded and in many places pass gradually into one another. It is probable that the coarse ejecta represent the products of eruptions of Peléan type, and that the bedded tuffs are due chiefly to explosions of Vulcanian type. The sands and gravels are doubtless the result of the washing and redeposition of these ejecta, partly during the actual eruptions and partly during the intervals of quiescence. That eruptions of Peléan and Vulcanian type can issue from the same crater within a single eruptive period is a phenomenon of common observation. It seems that at the Marysville volcano, the Peléan eruptions occurred when the motive force was exceptionally powerful, that is, when large volumes of steam had accumulated under high pressure in the conduit. Under such conditions, the bulk of the ejecta was so great and most of the fragments were so large, that they suffered little or no assortment by winds but fell onto the flanks of the cone as a single mass and descended in an avalanche-like manner, just as the *nuées ardentes* rushed down the slopes of Mont Pelée. When the eruptions were less violent, owing to a reduced pressure of steam, only small fragments were ejected, and these behaved as typical Vulcanian tuff-clouds. During their flight through the air, they underwent a gravitative separation, so that the heavier material fell first and nearest the vent while the lighter residue was carried to a distance by winds and was chiefly deposited about the base of the cone. The Vulcanian tuffs therefore exhibit a conspicuous lateral and vertical variation.

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[74] Tada, F., and Tsuya, H., The eruption of the Tokachidake volcano, Hokkaidô, on May 24th, 1926. Bull. Earthquake Research Inst., Tokyo Imperial University, vol. 2, pp. 49–85, March 1927.

[75] Howe, E., Recent tuffs of the Soufrière, St. Vincent. Am. Jour. Sci., ser. 4, vol. 16, pp. 317–322, 1903.

[76] Lacroix, A., *op. cit.* (note 70), pp. 375–379, 452–463, 1904.

It is, of course, impossible to estimate exactly how important a part water played during the deposition of the Peléan and Vulcanian ejecta at Marysville. To a certain extent, the Vulcanian tuffs that fell onto the cone must have been converted into mud by the action of rain, due to the condensation of steam; to some extent, also, the tuff may have fallen into streams and have dammed them to form mud flows. It is probable, however, that most of the Vulcanian ejecta were laid down in a dry condition. Moreover, the coarse, unbedded Peléan ejecta present no characters that suggest water to have been an essential factor in their mode of emplacement. The blocks among the Peléan breccias are almost invariably angular, and the fine matrix shows neither current-bedding nor any trace of having flowed as a true mud. A tumultuous mingling of fragments, ranging in size from that of sand to ten feet across, similar to that seen among the Marysville breccias, may be seen among the products of "dry avalanches" on Vesuvius and elsewhere. Such avalanches happen frequently owing to the sliding of incoherent ejecta on the steep sides of many volcanic cones, and may well have been an important process at Marysville.

The deposits left by the great mud flows that issued from near the summit of Lassen Peak in May 1915, are in many places well-bedded, many of their constituent fragments are rounded by torrential attrition, and there is considerable sorting of the finer materials. These features, which are notably rare among the Marysville breccias, suggest that the Lassen deposits were charged with a much higher content of water.

The characters of the Peléan rocks, with which the coarse breccias of Marysville are here correlated, have been admirably described by Lacroix.[77] Although some of the Peléan ejecta were re-worked by torrents and deposited downstream so as to reveal a more or less regular bedding and mechanical sorting, the bulk was entirely unstratified, and was deposited in an almost dry condition. The mud flows that occurred were secondary phenomena, due primarily to the damming of river channels. Lacroix's beautifully illustrated account of the Peléan deposits brings out in striking fashion their similarity to the coarse pyroclastic rocks at Marysville, strongly supporting the idea of a common mode of origin.

To recapitulate, the fragmental andesites that form the lower slopes of the Marysville Buttes, consist essentially of three types: first, coarse, unassorted breccias due to Peléan eruptions; second, well bedded, crystal, lithic and lapilli tuffs, due to Vulcanian explosions; third, sands and gravels due to the washing and reassortment of ejecta by streams both during the explosive periods and during the intervals of quiescence. These three types of deposit are irregularly interbedded, the individual beds generally ranging from a foot to fifteen feet thick, the breccia beds usually being much thicker than the tuffs. The steady quaquaversal dips of the rocks suggest at once that the ejecta issued from a central vent, and negative the idea of origin from a number of lateral craters, as Lindgren and Dickerson supposed.

VOLUME OF MATERIAL EJECTED

The present, even slope of the peripheral "tuff ring" of the Buttes is probably almost identical with the lower slopes of the volcanic cone at the close of the main eruptive period; in other words, if the present surface were projected over the laccolith, with a slightly increased dip toward the center, it would almost reprodce the form of the original cone. This residual surface is in many places over two miles wide, and shows an increase of dip from 5° to 12° when traced toward the laccolith. The nature of the ejecta is such that the slope near the top of the cone cannot have exceeded 30°. How far the andesite tuff and breccia extend beneath the alluvium of the Sacramento Valley, it is at present impossible to decide. Probably the beds thin out and disappear within a short distance; for example, a deep boring through the alluvium a quarter of a mile north of Pennington failed to reveal them. If the crater in the core of the laccolith be regarded as marking approximately the position of the top of the original cone, then the average thickness of the andesite tuff and breccia at a distance of two miles therefrom is about four hundred feet; at a distance of four and a half miles, it may be said to be almost negligible. Knowing the form of the pre-eruption surface with a reasonable degree of accuracy, it becomes possible to make at least a rough estimate of the volume of material thrown out. Making a liberal allowance for a large crater at the top of the cone, it seems that about four cubic miles of rock were ejected. The maximum height of the original cone was approximately 5000 feet.

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[77] Lacroix, A., *op. cit.* (note 70), p. 378, 1904.

MINOR ERUPTIONS

The foregoing descriptions apply to the products of the main explosions from the central crater. There were, however, other eruptions, both earlier and later, and these must now be considered. Some of these eruptions, like the main explosions, issued from the central crater in the core of the laccolith, but others appear to have been due to the blasting of lateral craters at and near the margins of the laccolith. The latter are definitely connected with adjacent intrusions of rhyolite porphyry.

Even at a distance, the pyroclastic deposits that abut on the northwestern and northeastern faces of North Butte are readily distinguishable from the brown and dark gray-weathering andesite breccias by reason of their whitish or pale gray color. This difference arises from the fact that the deposits are largely made up of fragments of rhyolite porphyry. On the northwestern face of the butte, for example, these fragments make up 75 per cent of the ejecta, the remainder being composed of angular pieces of sandstone from the Marysville formation, siliceous pebbles from the Butte gravels, Sutter tuffs, and rare blocks of andesite similar to that of the laccolith. The fine, tuffaceous matrix of this deposit consists of comminuted rhyolite porphyry and has the texture of sand. In many respects, it resembles the *pépéritic* margins of certain porphyry intrusions (*ante,* pp. 166–

169), and, like the *pépérites,* it is characteristically unbedded. Both the rhyolitic matrix and the larger fragments of rhyolite porphyry are identical with the porphyry of the intrusive mass immediately to the west (map). There can be little doubt, indeed, that this mixed deposit resulted from explosions which shattered part of the porphyry intrusion and the overlying sediments together with some of the adjacent andesite. Lack of continuous exposures and the unbedded character of the rhyolitic ejecta make it difficult to determine the precise relations of the deposit to the andesite breccia, but they are certainly of earlier date. Since they are only revealed below the andesite breccia in the immediate vicinity of North Butte, it seems that either the explosions were small and most of the ejecta fell near and back into the crater, or that if the ejecta were formerly more widespread they were largely removed before the main andesitic eruptions.

A deposit of somewhat similar character occurs approximately one-half mile southwest of Pugh Place, not far from the outlier of the sedimentary roof of the laccolith. Its outcrop is more or less oval, one-quarter mile long and about two hundred yards across. At its southwestern end, the deposit is partly enclosed by a vertical wall of massive andesite; elsewhere, the deposit is overlain by a thick covering of soil and its relations are obscure. Although presenting a general resemblance to the pyroclastic rocks about North Butte, especially in its high content of rhyolitic fragments, the deposit has many peculiarities. The matrix consists essentially of comminuted rhyolite porphyry and carries a great variety of inclusions. Especially noteworthy, is the abundance of hornblendic pebbles. These are generally similar to the hornblendic segregations found within the andesite of the laccolith, but exhibit greater textural variations than the segregations observed *in situ.* Some are coarse and gabbroid; others resemble pegmatites, or are partly schistose, and yet others are dense, aphanitic hornblendites. Accompanying these hornblendic pebbles, are fragments of the normal andesite, like that of the laccolith, pieces of sandstone and gray limestone, probably derived from the Marysville formation, and a large suite of pebbles from the Butte gravels. Although, on a large scale, the deposit is well-bedded, the constituent fragments are confusedly intermingled. Some of the coarser beds are ten feet thick, are unstratified within themselves, and carry fragments, up to the size of a fist, scattered in a matrix of rhyolitic dust. These beds appear to be the products of separate explosions. They are parted by layers of sand and gravel, which may show current-bedding, and by seams of clay, up to six inches thick. Most of this fine material was deposited in water and sorted. The dips at the southwestern end of the outcrop, near the wall of andesite, are toward the northwest at angles of 30° to 40°; elsewhere, they are generally toward the northeast at about 10°. It is probable that these dips have been imposed upon the beds by faulting and tilting, perhaps as a result of igneous intrusion below.

The vent from which this mixed deposit was erupted cannot be located: much of the adjacent country is heavily wooded and exposures are few. The fact that intrusions of rhyolite porphyry occur within a short distance, and that the only remnant of the roof of the laccolith and almost the only hornblendic segregations observed in place are within a quarter of a mile, suggest a near-by source for the deposit. Unfortunately, the position of the deposit offers no clue as to its age relative to that of the peripheral andesite breccias. The eruption occurred, however, when at least part of the laccolith was still beneath a thick sedimentary cover, including the Marysville and Ione beds, the Butte gravels and perhaps also a portion of the Sutter formation. It may have occurred as a direct result of the intrusion of the adjacent porphyry. Some of the ejecta may have fallen into crater lakes or into stretches of water in hollows on the surface of the laccolith; others may have been washed and sorted by streams. Such modes of deposition would explain the local presence of current-bedding and stratification.

Finally, about a mile southwest of West Butte, along the fault that throws the Chico beds against the Butte gravels, there is a conspicuous, wall-like mass of breccia, some seventy-five yards long in an east-west direction and up to forty yards wide. It consists of a confused mixture of angular and subangular blocks of andesite and of baked, white and gray mudstones and ferruginous, buff sandstones in a matrix of comminuted andesite and sand. Bedding is generally absent, but in places there is an obscure stratification that dips about 70° toward the northwest. The appearance of this mass suggests a breccia-filled pipe blasted through the Chico and Marysville beds and the underlying andesite. The breccia is so different from the andesite breccias erupted from the central crater, especially in its high content of sedimentary fragments, that it must have issued from a separate source.

FINAL ERUPTIONS: THE TUFFS INFILLING THE CENTRAL CRATER

Near the center of the laccolith occurs a remarkable development of pyroclastic rocks whose limit of outcrop, though very irregular, is roughly concentric with the outer margin of the laccolith and is about a mile in diameter. Where the rocks are observed in contact with the massive andesite of the laccolith, the plane of junction is invariably steep and is generally vertical. It follows, therefore, that the rocks occupy a more or less cylindrical depression inside the laccolith. This depression represents, without doubt, the crater from which was erupted the great accumulation of andesite breccia forming the lower slopes of the Buttes. Its present infilling is the product of the final explosions. Neither Lindgren nor Dickerson appear to have been aware of the existence of this infilled crater. Lindgren,[78] discussing the source of the peripheral ring of andesite breccia, says:

> Narrow gulches or defiles have been cut through this ring of mud flows, leading from crater-like valleys with level bottoms, which are often of roughly circular shape and surrounded by steep walls of tuff or massive andesite. Such craters are the two valleys 3 miles south of Pennington, that south of North Butte, and the South Butte Valley. There can hardly be any doubt that from these lateral craters a great deal, if not all, of the tuffs and breccias were ejected.

Dickerson, although recognizing that Lindgren's "lateral craters" appear to be erosion valleys in the sediments, merely ascribes the andesitic ejecta to a "central volcano."

The deposits that now occupy the central crater may be described comprehensively as bedded lithic tuffs. Indeed, the strong and regular stratification and the fineness of the constituents are, perhaps, their most conspicuous characters. Viewed from a distance, the bedding of the tuffs at the northern end of the crater is so pronounced as to give them a remarkable terraced appearance. The tuffs are excellently exposed to a thickness of 1000 feet, on the side of Bragg's Canyon (pl. 14*a*). In this northern part of the crater, the bedding is generally horizontal, or dips inward at the margins; to the south, however, it dips steeply toward the southwest edge of the crater (fig. 13). About the latter locality, the bedding is obscure and the precise attitude of the crater wall cannot be determined. At one place, however, it appears that a great pillar of andesite formerly protruded above the floor of the crater, being separated from the crater wall by a deep and narrow chasm.

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[78] Lindgren, W., U. S. Geol. Surv., Marysville Folio, no. 17, 1895.

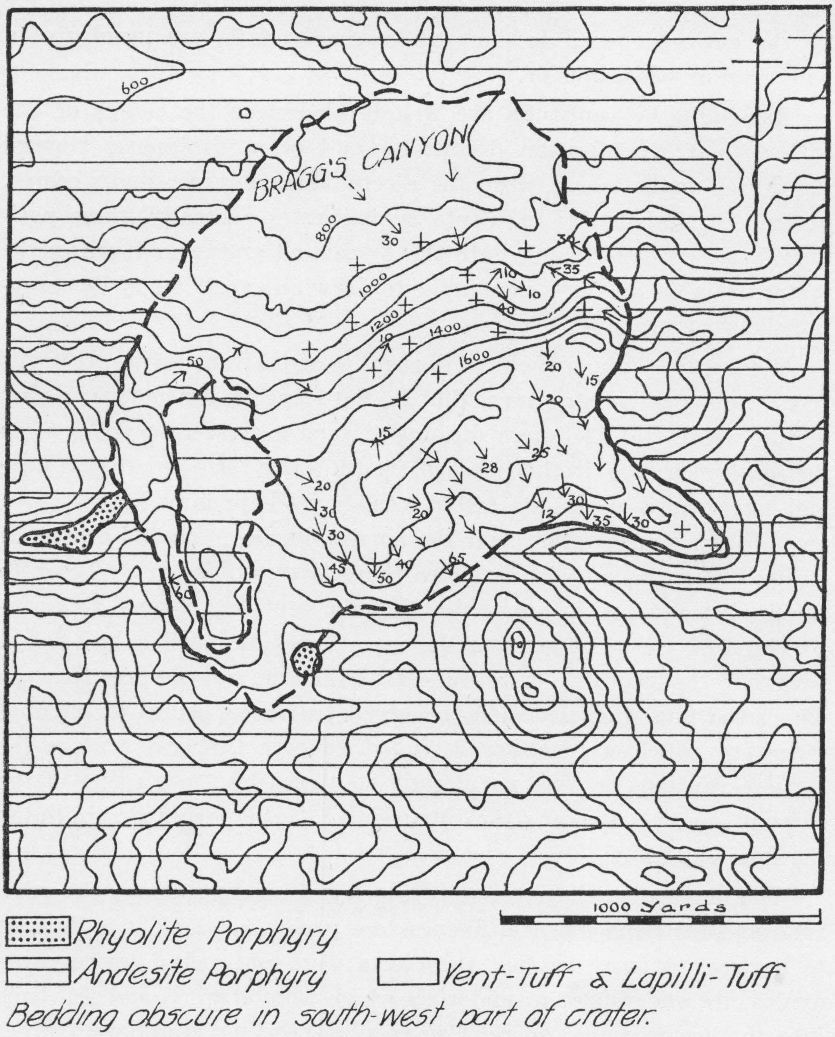

Fig. 13. Map of the central crater and environs.

The lithology of the tuffs infilling the crater contrasts strongly with that of the andesite breccias thrown out during the main eruptions. Within the crater, blocks exceeding three inches in length are rare. Most of the tuffs have the texture of coarse sand, and many resemble clays and silts in fineness. Moreover, they show a surprising unformity throughout large thicknesses, a feature which is never found among the peripheral andesite breccias. Finally, whereas the latter contain less than 1 per cent of non-andesitic ejecta, the average specimen of vent-tuff is half andesitic and half rhyolitic. In certain parts of the crater, fragments of biotite-rich rhyolite porphyry make up the entire deposit, and in such cases, the tuffs are usually of a pale gray or whitish color.

Although the vent-tuffs are well bedded near the center of the crater, their stratification diminishes and often disappears toward the crater walls, where, also, the ejecta become increasingly coarse, passing through lapilli tuffs into agglomerates. Locally, these peripheral agglomerates grade into the brecciated andesites forming the crater walls, so that it is impossible to draw an exact line of demarcation between them.

What were the conditions of deposition of the vent-tuffs? It seems from their general structure, that is, flat-lying in the northern part of the crater and elsewhere dipping toward a crescentic valley near the southwestern wall, that most of the tuffs were erupted from a long and narrow fissure at the latter locality. There may have been a second fissure of eruption near the northern wall of the old crater, in Bragg's Canyon, but the evidence there is unsatisfactory. Prior to the final explosions, it is probable that the vent was clogged by andesite breccia, the residue from the main eruptions, which had fallen back into the conduit. It appears, also, that the new fissures through which the final tuff-explosions occurred traversed bodies of rhyolite porphyry which were either intruded beneath the crater after the earlier eruptions or were not greatly shattered by the blasting of the original crater. Perhaps the intrusion of fresh porphyries initiated the final explosions.

The reasons for the extreme regularity of bedding among the vent-tuffs and for their uniform fineness are problems which it is difficult to answer. It may be that the ejecta were pulverized by repeated explosions, and represent materials which were erupted and fell back into the crater many times. The regular bedding is apparently not due to deposition in water, but to the gravitative sorting of the fragments during their flight through air. In a word, the vent-tuffs are of subaerial Vulcanian type. Considering the fineness of the tuffs produced by these last explosions, it can hardly be doubted that material similar to that now occupying the crater was carried long distances therefrom by winds and fell upon the andesite breccias of the earlier eruptions. But there is no trace of such a tuff sheet above the andesite breccias along the lower slopes of the Buttes; it must have been removed by erosion.

MICROSCOPIC CHARACTERS OF THE PYROCLASTIC ROCKS

A detailed account of the andesite tuffs and breccias is rendered unnecessary by their general similarity to the normal hornblende-mica andesite of the laccolith (pp. 150–152). For the most part, they are merely comminuted fragments of the laccolith and are wholly unaltered. Clearly, the temperature of eruption of such ejecta was comparatively low. Even the outermost parts of the rare ''bread-crust'' blocks fail to reveal any decomposition that can be ascribed to reheating, for the hornblende and biotite of the crusts retain the same greenish tints that are characteristic of those minerals in the unaltered andesites of the laccolith.

The tuffs and the fine, sand-like matrix of the breccias are essentially composed of mineral chips and minute, angular fragments of andesite, although toward the base of the succession, inclusions of rhyolite porphyry are also abundant. This upward diminution in the content of rhyolitic ejecta suggests that the earlier explosions broke through acid intrusions and that the later explosions passed almost entirely through andesite. Typically, the tuffs consist of broken pieces of andesine, oligoclase, green biotite, and hornblende in a dusty, feldspathic base, relieved by fragments of andesite and more rarely of rhyolite porphyry. Occasionally, there are glomero-porphyritic clusters of granular diopside, representing basic segregations blown out with the andesites. The latter, although mainly coarse in texture, like the typical andesites of the laccolith, are often highly feldspathic, and suggest local differentiation toward the top of the intrusion. Frequently, also, fragments of a pumiceous, colorless glass carrying grains of hornblende and biotite may be observed. These may well be due to the shattering of a thin, quickly chilled edge that formerly covered parts of the laccolith. The feldspar chips are intensely fractured, and the biotite flakes are often contorted and shredded, or have been bent against the sides of other phenocrysts. In almost all the andesite tuffs, the constituent crystals have optical properties identical with those of the minerals in the andesite of the laccolith, and appear to have been entirely unaffected by reheating. Occasionally, however, the minerals are decomposed and the ejecta assume a bright brick-red color, due to oxidation. Since these altered tuffs offer a clue as to the maximum temperature of the eruptions, it is necessary to discuss them in more detail.

Perhaps the best locality for the study of the oxidized ejecta is on "1559 Hill," about one and one-quarter miles S 15° E of North Butte, although reddened tuffs may be seen in thin bands here and there throughout the peripheral "tuff ring." The larger blocks of andesite have dark red crusts, that rarely exceed one-quarter inch in thickness. The biotite, which appears black in hand specimens of the fresh tuffs, assumes a bronze luster and the feldspar fragments are usually coated with rusty films of iron oxide. Viewed under the microscope, the alteration of the hornblende and biotite is seen to involve a change of color and a separation of magnetite. The mica loses its green tint and becomes increasingly brown and reddish brown as alteration proceeds, until it is finally replaced by magnetite. Simultaneously, the optic axial angle and birefringence increase. The hornblende also changes from green to brown and finally to black; its extinction angle diminishes from about 15° or 16° until it is straight, but in most sections the angle is about 3°, while its refractive index and birefringence increase. The pleochroism of the altered hornblende is usually from pale yellowish green to a deep reddish brown. The biotite usually shows X, yellow or greenish yellow, Y and Z, raw sienna or deep reddish brown, while its body color often exhibits a peculiar pinkish tinge. By reflected light, both the biotite and hornblende appear a bright brick red or show metallic streaks due to films of magnetite dust. In some crystals the magnetite segregates toward the margins, but in others it is concentrated in their cores (pl. 17, *a, b*).

The changes noted above, are attributed to oxidation and dehydration of the ejecta by reheating. It is probable that the liberation of the iron ores accounts for the rusty films seen on the surfaces of the feldspar crystals, and for the general red color of the altered tuffs. Neither the feldspar microliths nor phenocrysts exhibit any decomposition. The significance of these features as indices of the temperature of the pyroclastic eruptions are discussed separately below.

THERMAL STUDY OF THE ANDESITE

EXPERIMENTS TO DETERMINE THE TEMPERATURE OF THE PYROCLASTIC ERUPTIONS

Day and Allen,[79] in their attempt to determine the temperature of protrusion of the lava which rose into the crater of Lassen Peak in 1915 made a careful study of the biotite contained in the ejecta, and from its degree of alteration concluded that the lava "could not have been heated above 850° C after it approached the surface." Specimens of the lava were reheated in the laboratory to various temperatures: above 840° C, rapid decomposition of the biotite began, and at 1260° C the biotite completely disappeared. By this means, as it were employing biotite as a "geological thermometer" and by contrasting the artificially altered rocks with those naturally heated in the crater, an approximate figure for the temperature of the eruption was obtained. The record of these experiments suggested that a similar study might indicate, even if roughly, the temperature of explosion of the pyroclastic rocks at Marysville.

For the purposes of the experiments on the Marysville andesite, specimens of the coarsely porphyritic, gray andesite from near West Butte were selected. Some of these were heated under oxidizing conditions for periods ranging up to three hours and to various temperatures reaching a maximum of 1150° C. Other specimens were heated under neutral conditions, that is, in the presence of carbon dioxide and steam, for periods of up to four hours' duration and to a maximum temperature of 1135° C. The andesite was first crushed to an average grade-size of 1 mm., a degree of comminution, which, though isolating many phenocrysts, left others embedded in their feldspathic matrix. It was thus possible to ascertain in the heated specimens whether or not reactions took place between the phenocrysts and their groundmass. The crushed andesite was placed in "boats" within a long silica-tube; by this means it was possible to pass a continuous stream of steam and CO_2 over them during heating. Probably, this neutral atmosphere was not very different from that in which the andesites were actually reheated prior to their explosion from the volcanic conduit. The experiments in air were undertaken to determine the maximum temperature to which the andesite was naturally reheated under oxidizing conditions, such as might obtain after the main steam explosions or during intervals of repose between successive eruptions.[80]

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[79] Day, A. L., and Allen, E. T., *op. cit.*, pp. 49–51, 1925.

How far the results described below would be modified by a repetition of the experiments under high pressures, it is difficult to say, but it is probable that the actual vapor pressures in the volcanic conduit were only high in depth, and that most of the reheated ejecta blown out of the upper parts of the conduit were never subjected to great pressure. The influence of time upon the alterations of the andesite in the conduit is also one which it is impossible to assess with accuracy. It seems certain, however, that the periods of reheating to which the rocks were subjected in the laboratory were very much shorter than those to which the tuffs and breccias were naturally subjected. The estimates of the temperature of eruption made upon the laboratory tests may therefore be taken to represent maxima; many changes produced in the andesites at high temperatures in the laboratory would probably be reproduced at much lower temperatures under high vapor pressures and with longer periods of reheating.

Experiments under oxidizing conditions.—When the crushed andesite was heated in air for two and one-half hours to a temperature of 540° C, no appreciable changes were observed, beyond the development of a brassy luster on the biotite flakes and a pink coloration on the surfaces of the feldspars, as if due to the oxidation of microscopic particles of iron ore. When, however, the rock was heated for the same length of time at 565° C, there was, in addition to the above alterations, a patchy change in the color of a few hornblende crystals from green or bluish green to dark olive green.

More notable changes resulted from the heating of the andesite for a period of only one-half hour to a final temperature of 620° C. The biotite assumed a deep reddish brown or raw sienna color, with irregular black clouds of magnetite; the hornblende exhibited an incipient change in a few crystals, the normal bluish green tint of the mineral giving place to a deep olive green color dappled with brown. Such crystals showed an almost complete absorption parallel to Z, and their extinction angle, $Z \wedge C$, was as low as 3°. Other hornblende crystals had a pleochroism from citrine, X, to orange citrine, Z, and an extinction angle, $Z \wedge C$, of 9°. This lowering of the extinction angle of the hornblende and the deepening of color represent the first stages in the passage to true basaltic hornblende.

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[80] The experiments were carried out with the kind help of Professor W. C. Blasdale in the Department of Chemistry and of Professor W. S. Morley in the Department of Metallurgy. The writer is greatly indebted for the facilities which they so readily placed at his disposal.

Heated in air for an hour to a temperature of 860° C, the green hornblende was almost entirely altered to a deep brown variety, showing a dominant pleochroism from cadmium yellow or orange, *X*, to deep burnt sienna, *Z*, and an extinction angle, $Z \wedge C$, of 2°. This condition of the hornblende is to be seen in some of the actual andesite tuffs and breccias. Many crystals, however, even on the thinnest edges, appeared black, probably owing to superficial films of magnetite. It is noteworthy that this separation of magnetite resulted in the formation of irregular black clouds, whereas in the naturally reheated tuffs and breccias, the liberated magnetite tends to follow and outline the cleavage-planes of the hornblende. The biotite was frequently blackened over its entire surface, and was usually of a still deeper and more reddish body-color. Its optic axial angle had also widened notably. Both the feldspathic base and the plagioclase phenocrysts were quite unaltered.

Heated for two and one-half hours at 910°C, it was found that the extinction angles of all the hornblende crystals had been reduced from 15° or 17° to 2° or 3°. Simultaneously, the refractive index rose from 1.68 (γ) in the fresh, green hornblende, to 1.73 (γ), and the birefringence rose from 0.019 to above 0.040. The lowering of the extinction angle of the hornblende with increase of temperature was at first rapid and then slight. Even at 620° C many of the crystals extinguished at 3°.

When subjected to a temperature reaching 1050° C for a period of one and one-half hours, almost all the biotite and hornblende crystals appeared jet black, even on the most delicate edges, and exhibited a rusty brown reflection, while some of the hornblende showed a pleochroism from deep burnt sienna to black. At this temperature, also, the feldspathic base revealed an incipient clarification and passage into glass. This clarification is ascribed to a segregation of magnetite dust into larger and more discrete particles and to a concentration of finely divided ferromagnesian pigment.

The changes just referred to were accentuated by further heating, namely, for two hours to 1080° C. The proportion of colored minerals became even smaller and there was an increased clarification of the feldspathic matrix. Viewed under high power and in ordinary light, the glass developed in the matrix appeared to have a vermicular or graphic texture, perhaps due to a finger-like intergrowth of glasses of slightly different refractive indices, such as might result from the solution of plagioclase microliths in a felsitic base. In the andesites heated at 1150° C for three hours, this vermicular texture of the matrix was less pronounced, as if the solution of the microliths had been more advanced. Throughout these changes, the porphyritic feldspars were unaffected. The inference may be allowed that the lower melting point of the matrix is due to the admixture of microscopic particles of magnetite and ferromagnesian minerals. The glass produced at 1150° C had a refractive index of 1.505, which, according to George,[81], indicates the following contents: Silica, 70 per cent; MgO, 1.5; K_2O, 4; iron oxides, 4; CaO, 2 per cent. The glass is thus much more acid than the porphyritic feldspars, and is also more acid than the bulk composition of the andesite (analyses 1 and 2).

The alterations induced in the andesite by heating in air are probably the combined result of oxidation and dehydration, but it seems that oxidation itself is not the essential factor, for similar changes were produced, though at higher temperatures, under neutral conditions.[82] A comparative study of the specimens described above with the andesite tuffs and breccias erupted at Marysville makes it clear that the latter were, for the most part, never heated under oxidizing conditions to a temperature of more than 600° C, and that few if any of them were thus heated above 700° C. There is, indeed, nothing to disprove the idea that most of the ejecta were only heated in air at temperatures far below 600° C.

Experiments under neutral conditions.—After heating in an atmosphere of steam and CO_2 for a period of two and one-half hours at 540° C, the andesite was still unaltered. Distinct changes were observed, however, when the rock was heated at 800° C for an hour. Many of the biotite flakes were reddened and some were mottled by the separation of magnetite, while the color of the hornblende crystals showed an incipient change from green to brown, though the birefringence and extinction angles of the crystals were not appreciably modified. Heated at temperatures between 810° C and 850° C for two hours, the green hornblende was entirely changed to deep brown and brownish green varieties and in some crystals was so deeply colored as to appear brownish black on the thinnest edges. Most of the altered hornblende had a pleochroism from olive green or pale brownish green to deep reddish brown or raw sienna, a pleochroism typical of the hornblende in many of the Sierran andesites and in the andesite tuffs of the Sutter formation. In most cases, the birefringence was about 0.040 and the extinction angle, $Z \wedge C$, varied from 2° to 4° and occasionally the extinction was straight. In other words, the hornblende presented all the optical characters of true basaltic hornblende. At these temperatures, 810° C to 850° C, also, the biotite was strongly mottled in browns and blacks by the diffusion of magnetite, but the feldspars were unaffected. After an additional two hours' heating at temperatures between 920° C and 960°C, almost all the hornblende and biotite was thoroughly decomposed and appeared black. A few hornblende crystals developed a pleochroism from a pale yellow green or leek green to deep Indian red or russet; these crystals were straight-extinguishing and had a birefringence of about 0.045, and granular magnetite was segregated along their cleavage laminae. Incipient solution of the microlithic, feldspathic base set in after heating for one and one-half hours at temperatures between 980° C and 1020° C, while an additional heating for one and one-half hours at 1100° C to 1135° C rendered the base almost wholly glassy. At these high temperatures, only rare grains of hornblende and biotite retained any color, but the feldspar phenocrysts were still unaltered, except for a slight marginal decomposition where they were imbedded in the glassy matrix.

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[81] George, W. O., The relations of the physical properties of natural glasses to their chemical composition. Jour. Geol., vol. 32, pp. 353–372, 1924.

[82] Cf. Graham, W. A. P., Notes on Hornblende. Am. Mineralogist, vol. 11, pp. 118–123, 1926.

A comparison of the alterations effected by artificial reheating of the andesite with those seen in the actual andesite tuffs and breccias ejected from the central crater at Marysville suggests that the latter rocks can never have been reheated under neutral conditions to temperatures much above 800° C. Indeed, none of the Marysville ejecta exhibit such an advanced stage of alteration as that produced in the laboratory by reheating the andesite for only two hours at temperatures between 810° C and 850° C. Moreover, most of the Marysville tuffs and breccias are wholly unaltered or comparatively fresh, and these may never have been heated in a neutral atmosphere above 500° C or 600° C. Prolonged reheating of the ejecta prior to explosion from the crater might well produce the observed alterations at temperatures far below those at which similar alterations were induced experimentally.

The conclusion from these studies is, therefore, that the Marysville tuffs and breccias were never heated in air at a temperature higher than 600° C and in a neutral atmosphere at a temperature higher than 800° C. By far the greater part of the ejecta is quite unaltered and could only have been reheated at a comparatively low temperature. The maximum temperatures just quoted are very liberal estimates, for they are based on the assumption that the periods of reheating in the crater were short. The observed alterations of the ejecta may have been produced at much lower temperatures owing to more prolonged periods of reheating and to high vapor pressures within the conduit.

DENUDATION SINCE THE VOLCANIC EPISODE

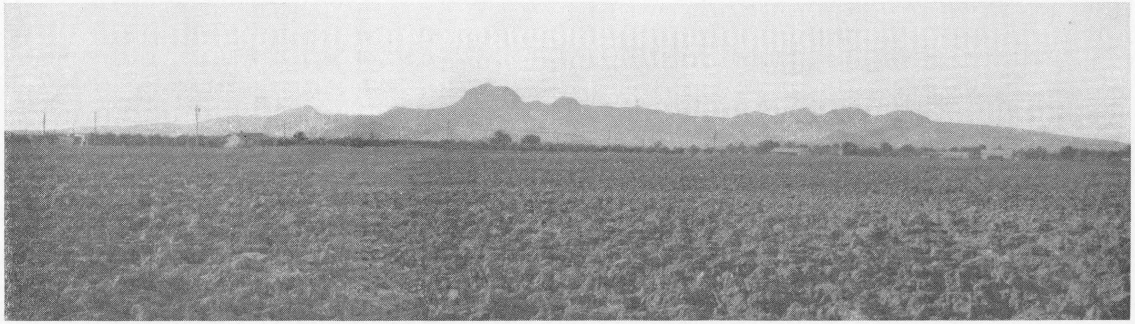
At the close of the period of volcanic activity, the cone probably reached an elevation of about 5000 feet above the present sea level. At first, the drainage was doubtless radial, but once the cover of volcanic ejecta had been penetrated to its base, the drainage must have been influenced by the old channels that had been cut on the flanks of the laccolith prior to the volcanic eruptions. In other words, a radial drainage developed on the surface of the cone until it was affected by an older drainage system incised on the laccolithic dome. Where the present streams traverse the andesite tuffs of the old cone, they are radial with respect to the center of the Buttes, but where they cross the sedimentary ring they are often concentric, following the strike of the upturned beds, or are localized by zones of faulting. Within the laccolith, the drainage is again chiefly radial; there, however, it is more irregular and may be partly determined by zones of brecciation among the igneous rocks. Numerous small streams are now cutting backwards from the base of the old cone, and some of these have already broken through to the sedimentary ring so as to tap the subsequent, annular drainage. Ultimately, however, as degradation proceeds, the Buttes will be reduced to insignificant hills and the peripheral slopes of andesite tuff will disappear. Then the concentric drainage, following the strike of the upturned sediments, will become predominant, and, save for the central crater in the core of the laccolith, the signs of a former volcano will forever be lost.

EXPLANATION OF PLATES

EXPLANATION OF PLATE 9

a. General view of the Marysville Buttes from near Sutter City, showing the even slope of the peripheral tuff ring, the eroded ring of sediments, and rugged, laccolithic core.

b. Looking west along West Butte Pass. The hills in the foreground are of Butte gravels, standing vertically. The pass is cut in the soft Sutter tuffs and sands. In the distance, on the right, is an intrusion of rhyolite porphyry; on the left are hills of andesite breccia, part of the original volcanic cone.



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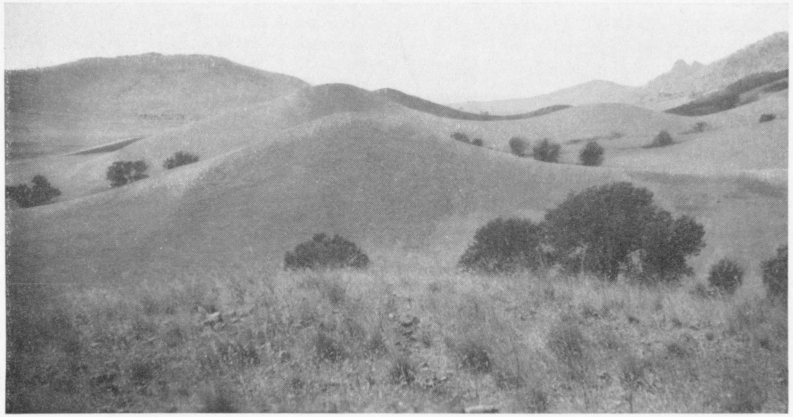


b

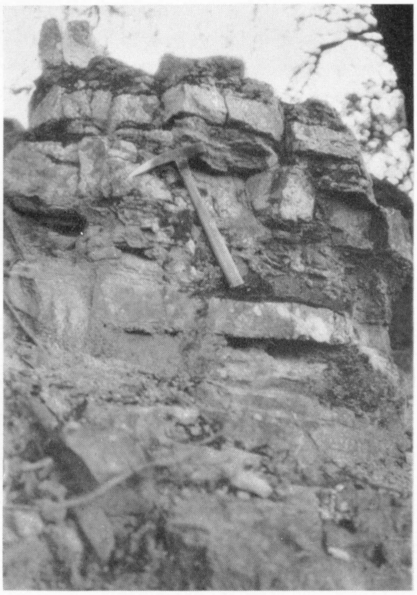
EXPLANATION OF PLATE 10

a. Rhyolite porphyry auto-brecciated in bands. Near the margin of the intrusion by De Witt's quarry, northwest of Sutter City. Photographed by F. A. Moss.

b. Auto-brecciated edge of rhyolite porphyry intrusion, near Kellog's Ranch, northwest of Sutter City. Photographed by F. A. Moss.

c. Auto-brecciated andesite porphyry. One mile northeast of South Butte. Photographed by V. T. Allen.

d. Cavernous weathering in vent-tuff; southeast corner of the crater. Photographed by F. A. Moss.



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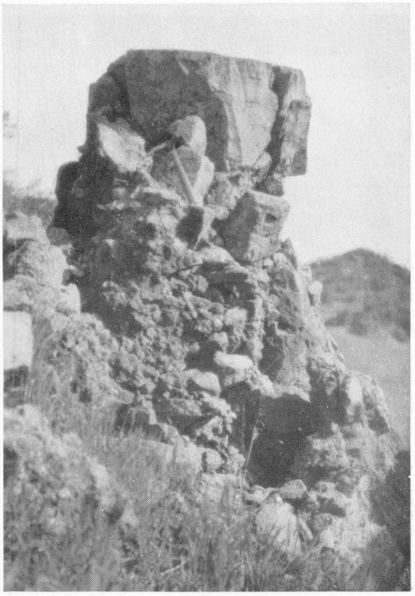

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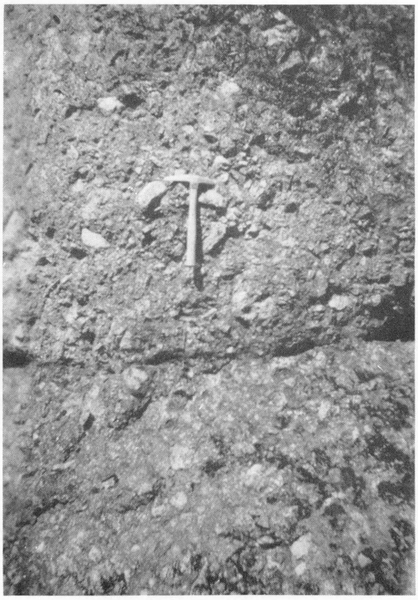

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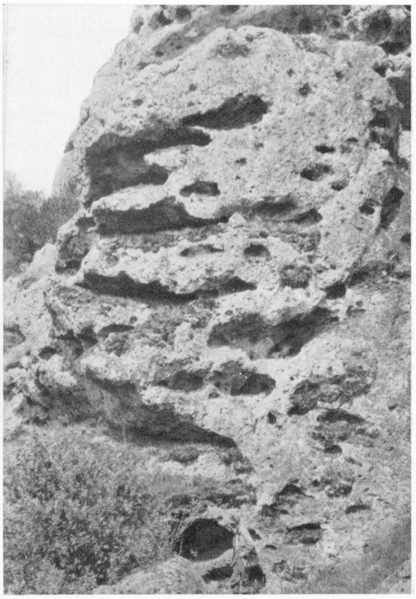


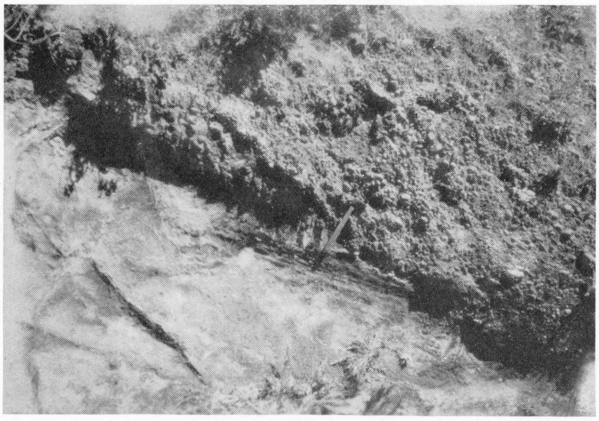
d

EXPLANATION OF PLATE 11

a. Disconformable contact of the Butte gravels on the Ione sands, near Kellog's Ranch, northwest of Sutter City. Photographed by F. A. Moss.

b. Rhyolite porphyry intrusion, ''850 Hill,'' near Pugh Place, north side of the Marysville Buttes. The intrusion is surrounded by sediments; the hills beyond are of andesite breccia, part of the original volcanic cone; the foreground is part of the andesitic laccolith. Photographed by F. A. Moss.

c. Banded edge of rhyolite porphyry intrusion, near De Witt's quarry, northwest of Sutter City; to show the arching of the banding toward the top of the intrusion. Photographed by F. A. Moss.



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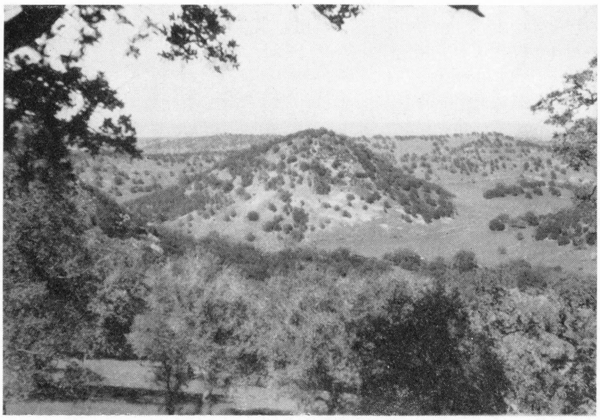


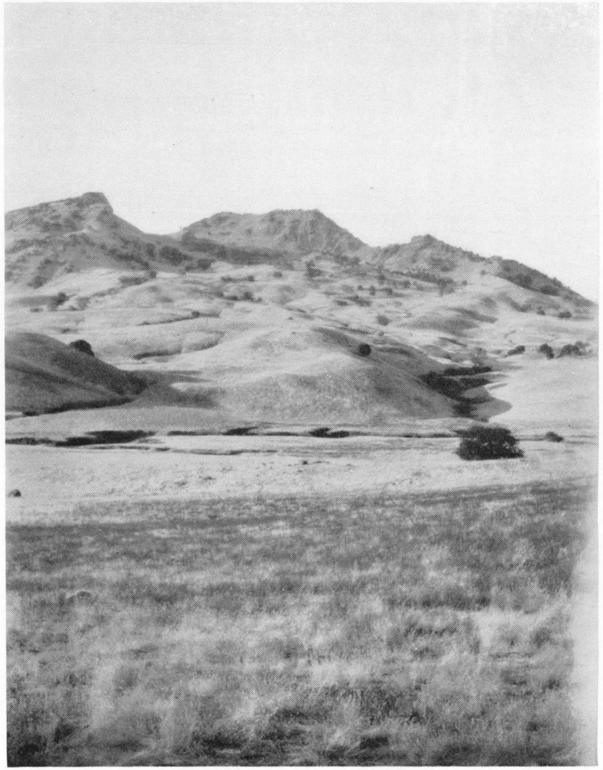
b

c

EXPLANATION OF PLATE 12

a. Part of the sedimentary ring and laccolith on the southeast side of the Buttes. A north-south fault runs parallel to the length of the photograph through the bush in the foreground. The foreground itself is composed of Sutter tuffs; the first low hills are of Butte gravels; the Ione sands and Marysville beds lie nearer the laccolith. The skyline ridge forms part of the laccolith. A plunging anticline lies to the left (west) of the fault.

b. Ione sands. One mile south of South Butte. Dip to the left (south) at 65° to 70°.



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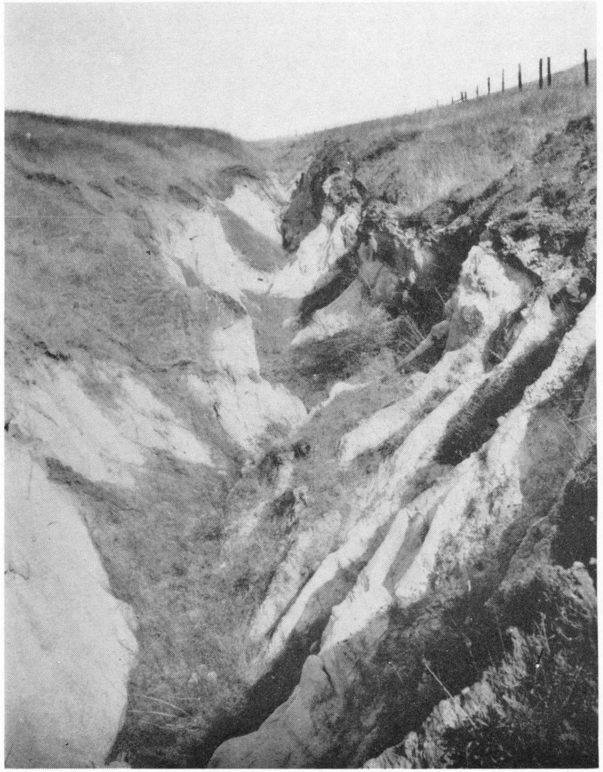
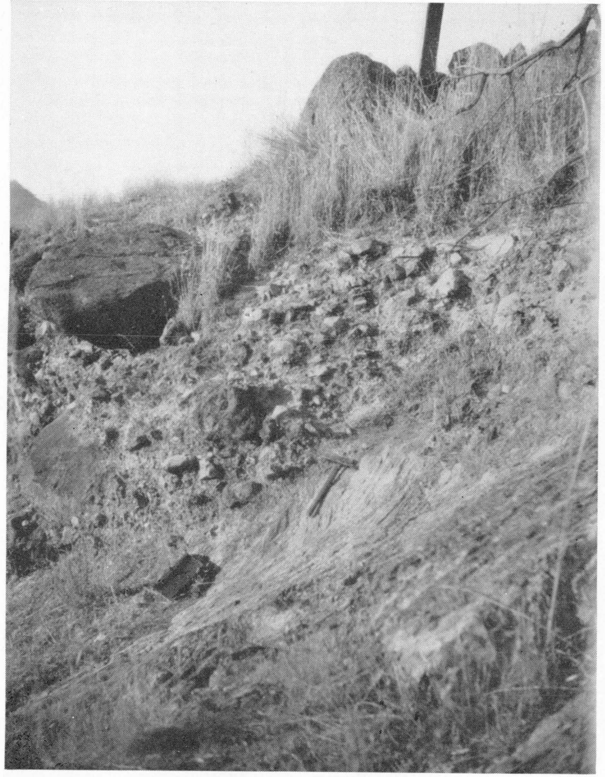


b

EXPLANATION OF PLATE 13

a. Andesite breccia carrying blocks of rhyolite on an old, weathered surface of rhyolite porphyry, along the north-south fault valley, near de Witt's quarry, northwest of Sutter City.

b. Typical topography of the andesite breccias; andesite tuff in the foreground. North side of the Marysville Buttes.



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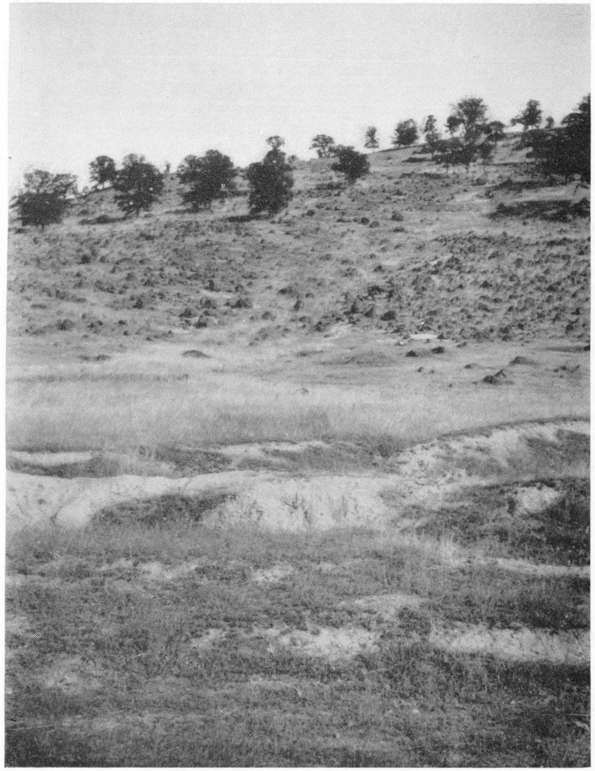
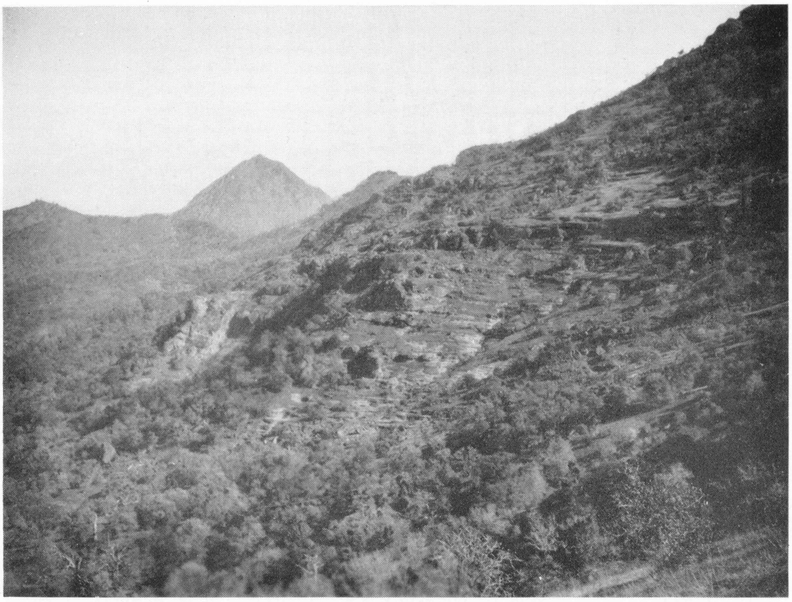


b

EXPLANATION OF PLATE 14

a. Bedded vent-tuffs on the south side of Bragg's Canyon. North Butte, part of the laccolith, in the background.

b. Coarse andesite breccia resting on an uneven surface of fine andesite tuff. South side of ''1000 Hill,'' east side of the Marysville Buttes.



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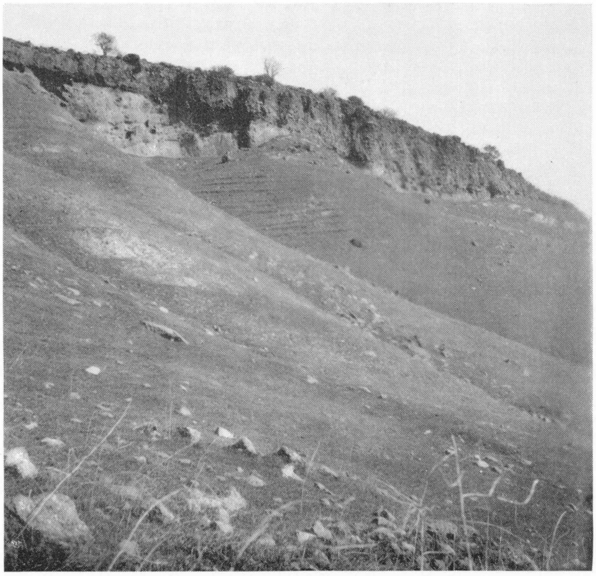


b

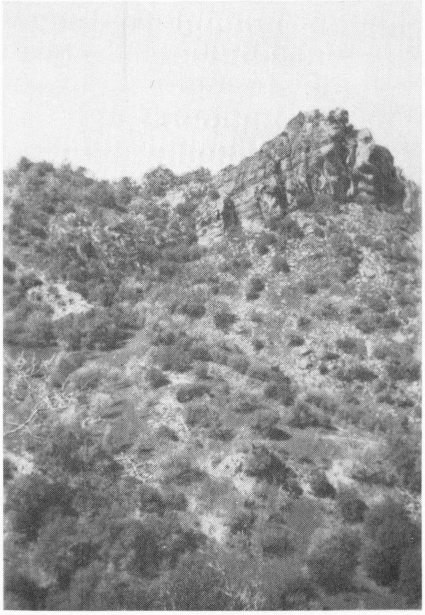
EXPLANATION OF PLATE 15

a. Bedded rhyolite and andesite tuffs and gravels of the Sutter formation; southeast side of ''1559 Hill,'' east side of the Marysville Buttes. Photographed by V. T. Allen.

b. Banded andesite porphyry (dipping WNW) within the laccolith, near Pugh Place, north side of the Buttes. Photographed by V. T. Allen.

c. Columnar jointing in andesite porphyry on the south side of ''1559 Hill,'' east flank of the Buttes. Photographed by F. A. Moss.

a



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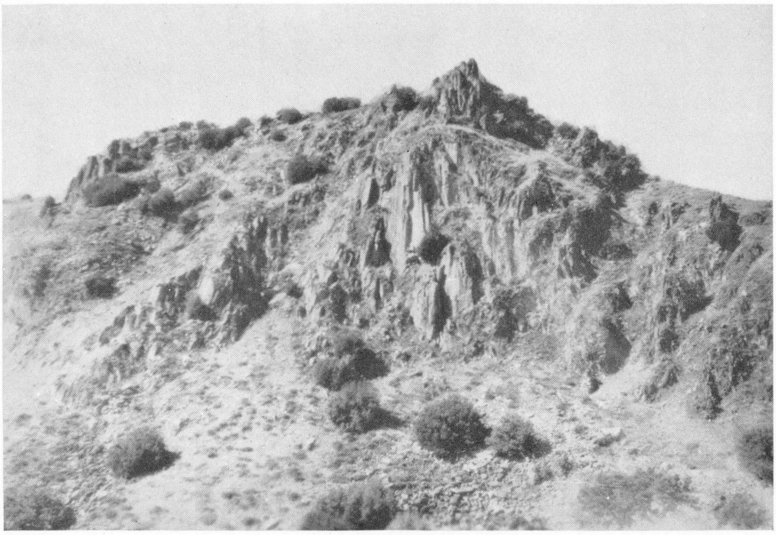
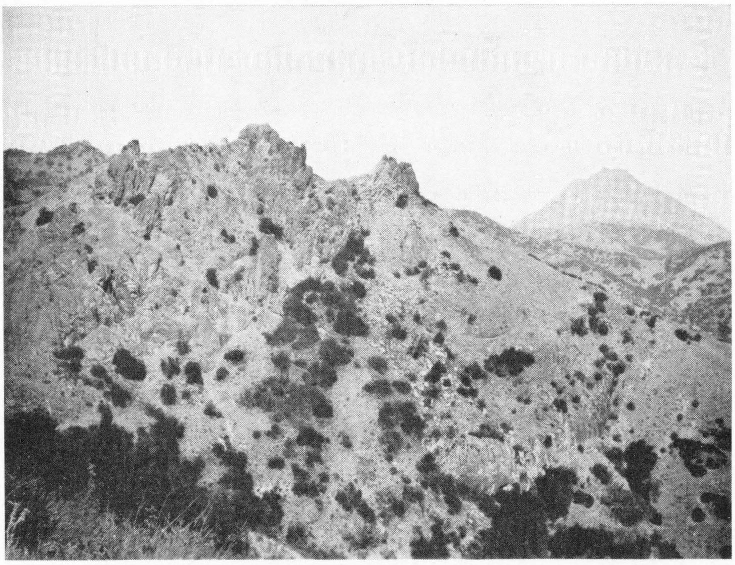


c

EXPLANATION OF PLATE 16

a. Typical view within the andesitic laccolith. Looking north toward North Butte in the distance.

b. Auto-brecciated (*pépéritic*) rhyolite porphyry. East-west gully, north of de Witt's quarry, three miles northwest of Sutter City.



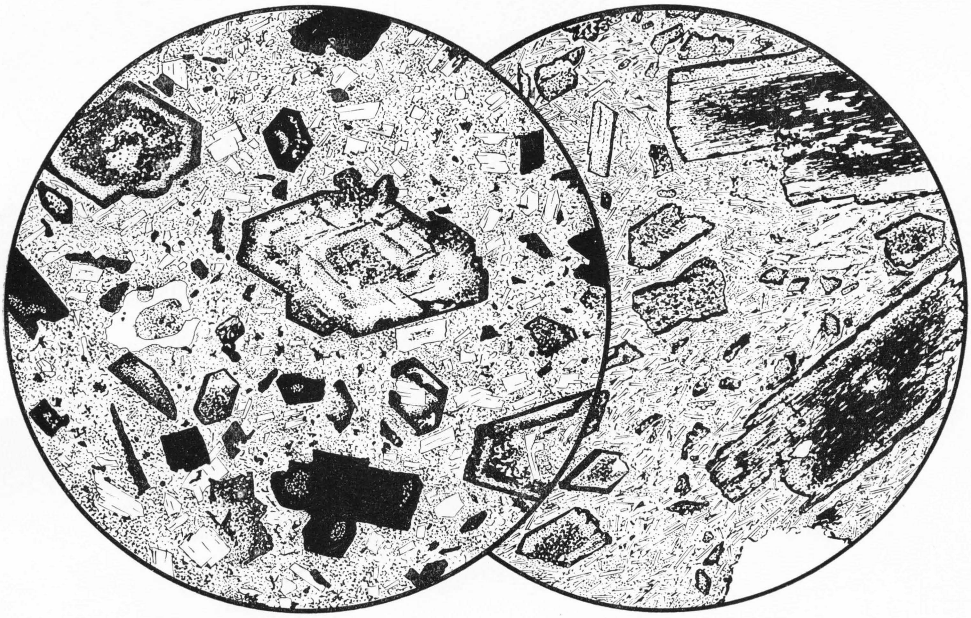
a

b

EXPLANATION OF PLATE 17

a and *b*. *Andesitic ejecta*. *a,* Hornblende-mica andesite crystal tuff (16). Matrix of andesite breccia, south of West Butte Pass. Showing decomposition of the ferromagnesian constituents. Note magnetic pseudomorphs after hornblende. The base is of oligoclase microliths with interstitial feldspathic material clouded with magnetite dust. × 40. *b,* Fragment of andesite breccia (47). East side of the Buttes, near "1559 Hill." Showing segregation of magnetite in the cores of the altered hornblende phenocrysts. The ferromagnesian constituents have lost their normal green color and are brown or reddish, due to reheating prior to explosion. × 40.

c and *d*. *Sutter tuffs*. *c,* Detrital andesitic lithic tuff (21). From near the road through West Butte Pass. Fragments of glassy, labradorite andesites, and brown hornblende andesite (center of field) in a matrix of calcite with broken crystals of feldspar and hypersthene (H). × 34. *d,* Rhyolitic vitric tuff (15). From the base of the Sutter formation, near the road through West Butte Pass, south of South Butte. Fragments of rhyolitic pumice and broken crystals of orthoclase and albite in a matrix of rhyolitic glass-dust stippled with magnetite. × 34.



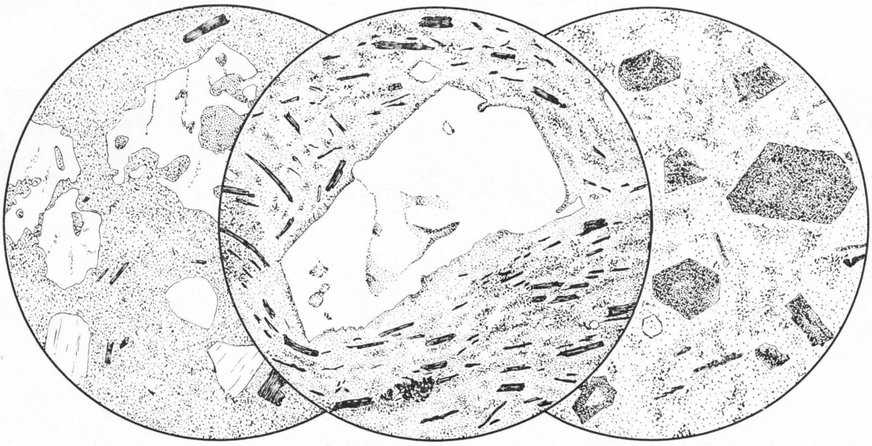
a *b*

c *d*

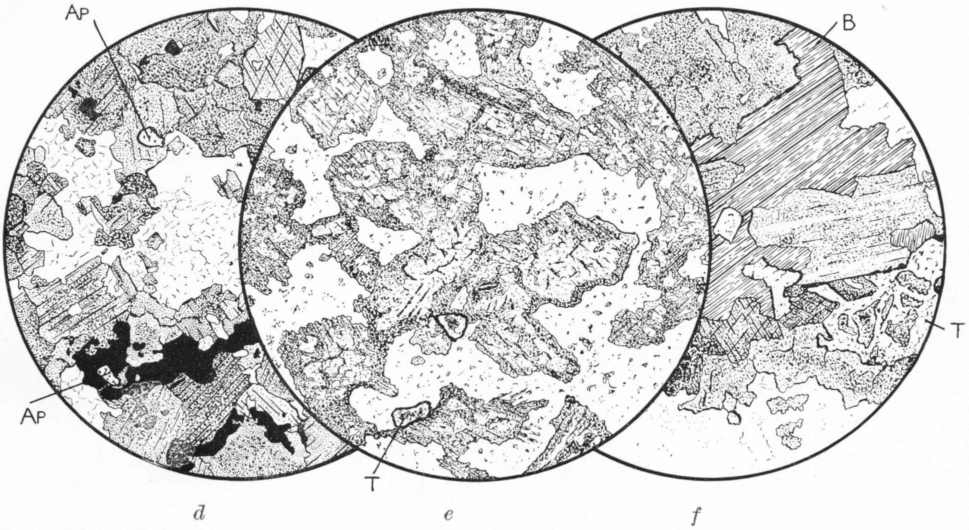
EXPLANATION OF PLATE 18

a, b, and *c.* Rhyolite *porphyries.* *a,* From near the top of ''495 Hill,'' north of Keenan's Ranch House, northwest side of the Buttes (63). Rounded and embayed crystals of orthoclase and angular crystals of albite (showing cleavage) with ragged flakes of brownish green biotite in a microfelsitic base. × 15. *b,* From near Moore's Ranch House, on the southeast margin of the laccolith (40*a*). Phenocrysts of orthoclase and flakes of greenish brown biotite, showing a fluxional arrangement, in a microfelsitic base of quartz and orthoclase. Dusty magnetite, partly limonitized, segregated parallel to the flow-planes. × 15. *c,* From the same locality as *b.* Section cut parallel to the flow-planes, showing the flat-lying arrangement of the biotite flakes. A micrographic-granular base of quartz and untwinned acid plagioclase and orthoclase, with a cross-section of an apatite crystal. Irregular blotches of magnetite dust. × 15.

d, e, and *f. Hornblendic Inclusions.* *d,* Hypidiomorphic to granular intergrowth of green hornblende and magnetite and granular, untwinned labradorite, with apatite (Ap). × 28. *e,* Pale green diopside surrounded by rims of green hornblende, with interstitial, untwinned labradorite carrying ragged grains and microliths of diopside. Accessory titanite. Analysis no. 9, p. 157. × 28. *f,* Hypidiomorphic-granular intergrowth of green hornblende, with brown biotite (B) and labradorite. Accessory apatite and titanite. × 28.



a *b* *c*



d *e* *f*

EXPLANATION OF PLATE 19

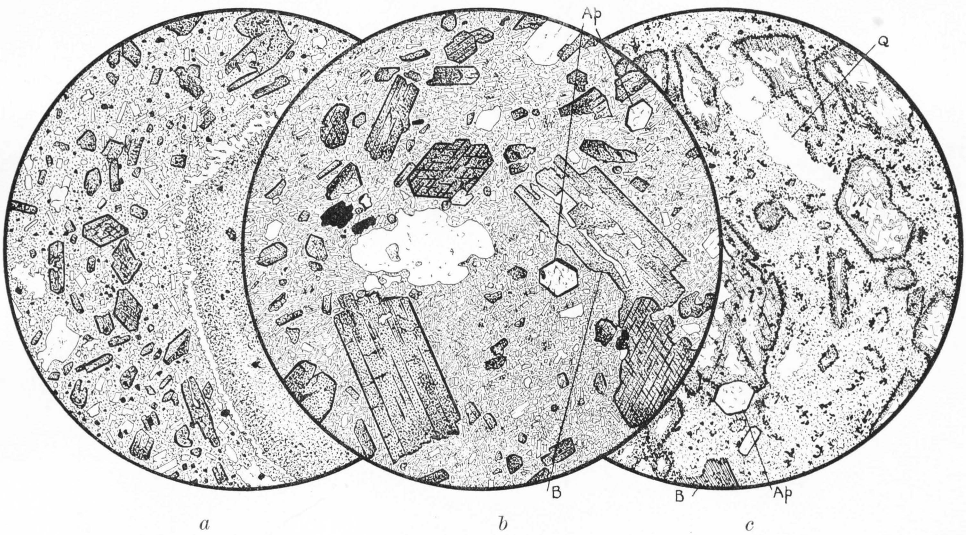
a. Hornblende-mica andesite porphyry (74); one mile west of South Butte. Resorbed phenocrysts of acid plagioclase with clear, glassy rims and cloudy, dust-charged cores; phenocrysts of pale green hornblende; hyalopilitic base, studded with granules of magnetite. Analysis no. 2, p. 154. × 32.

b. Hornblende-mica andesite porphyry (62); ejected block from the north side of ''547 Hill,'' near West Butte. Phenocrysts of green hornblende and brownish green biotite (B), resorbed acid plagioclase and accessory apatite (Ap) in a pilotaxitic base, rich in microliths of oligoclase. × 32.

c. Propylite (29); near the margin of the laccolith, south of West Butte. Phenocrysts of hornblende replaced by chlorite and calcite and outlined by granular magnetite; accessory biotite (B) and apatite (Ap); matrix of decomposed cryptofelsite relieved by clear patches of secondary quartz mosaic (Q). Analysis no. 6, p. 154. × 32.

d. Hornblende-mica andesite porphyry (79); part of the ''breadcrust'' of an ejected block, from the southeast margin of the Buttes, two and one-half miles WNW of Sutter City. Showing hornblende phenocrysts (one with a nucleus of colorless diopside (*D*), brownish green biotite and porphyritic oligoclase in a feldspathic, partly glassy base carrying microliths of oligoclase. × 43.

e. Hornblende andesite porphyry (52); west side of West Butte. Large phenocrysts of oligoclase with zonally arranged inclusions of dust and glass in a hyalopilitic base carrying pale green crystals of hornblende and accessory apatite (Ap). × 43.


Ap
Q
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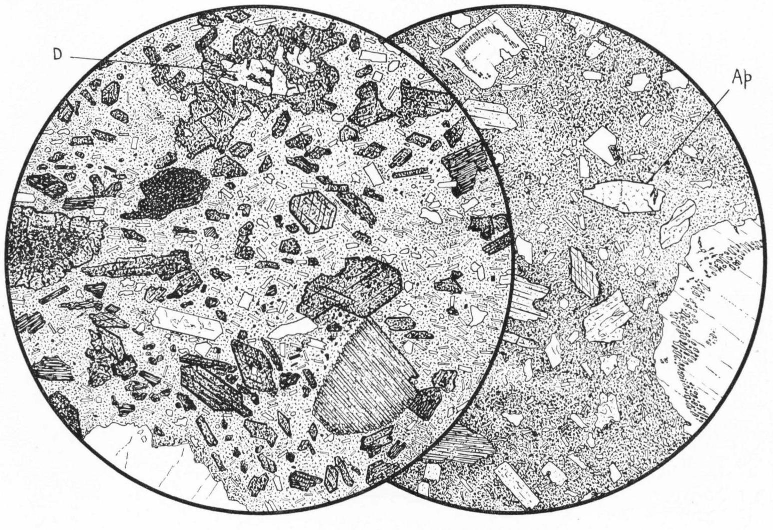
D
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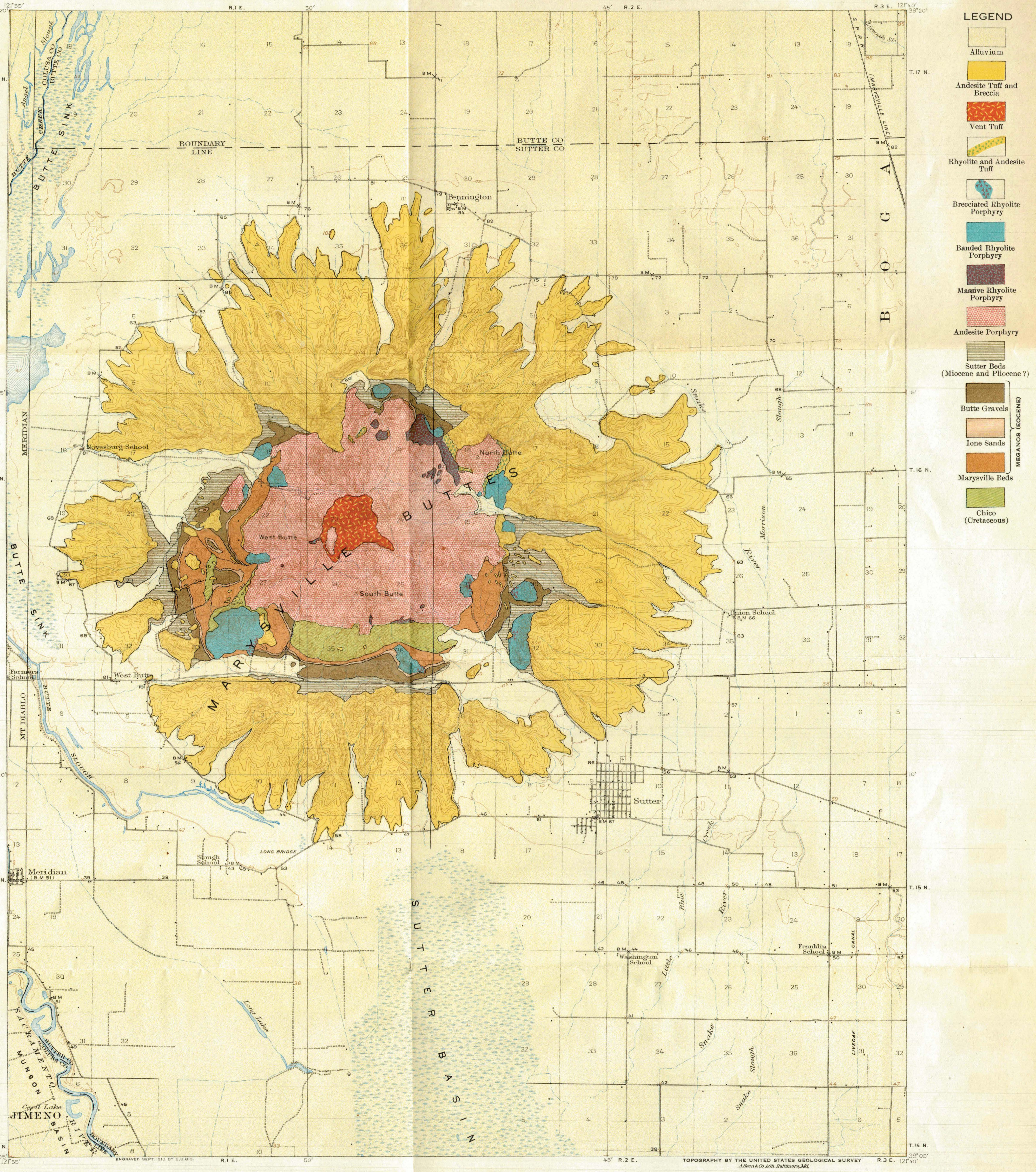
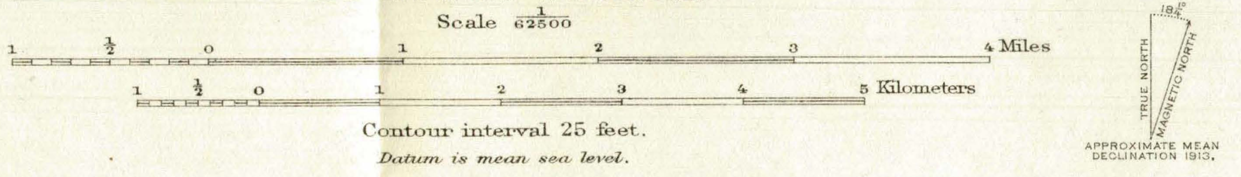
GEOLOGICAL SOCIETY OF THE OREGON COUNTRY



GEOLOGIC MAP OF THE MARYSVILLE BUTTES, CALIFORNIA

BY HOWEL WILLIAMS

Scale $\frac{1}{62500}$



Contour interval 25 feet.

Datum is mean sea level.